AMRL-TR-70-60

THE USE OF COMPUTERS FOR MAN-MACHINE MODELLING: STATUS AND PLANS

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JUNE 1970

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WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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1100 - September 1970 - CO190 - 5-71-[illegible]

FOREWORD

This report documents a panel session which was organized by Mr. Gerald P. Chubb at the request of Dr. George Rowland, Technical Program Chairman for the 13th Annual Human Factors Society Meeting held in Philadelphia 13 - 15 October 1969. Since the proceedings of this meeting were not published, this document has been prepared to provide authorship credit to the participants and to satisfy the need for distribution copies, since several requests have already been made to date.

Special acknowledgment and recognition must also be given to the several discussants of the papers presented. Dr. Arthur D. Siegel provided some additional commentary on digital simulation, extending and refining some of the statements made in Dr. Wolf's paper. Dr. Lowell Schipper discussed some of the reasons for needing the integrative framework provided by Dr. Schrenk's paradigm for decision making. Although Dr. Joseph Rigney was unable to attend the meeting, he did review Mr. Ryan's work rather extensively and prepared a written discussion which was read by Mr. Chubb. All of the participants were most cooperative, and despite their own normally busy workload, all managed to meet the almost impossible deadlines that were imposed on them. Hopefully, this technical report will provide professional recognition of their efforts in extending the state-of-the-art in modelling the human factor, in and out of a specific system or design context.

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio 45433

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP
N/A

3. REPORT TITLE
The Use of Computers for Man-Machine Modelling: Status and Plans.

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name) Gerald P. Chubb, Aerospace Medical Research Lab.; Julia T. Apter & William W. Graessley, Presbyterian-ST. Luke's Hospital; Lorenz P. Schrenk, Honeywell, Inc.; J. J. Wolf & Arthur I. Siegel, Applied Psychological Services; Patrick W. Ryan, The Boeing Co.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1970	70	62

8a. CONTRACT OR GRANT NO.

b. PROJECT NO. 7184/09

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
AMRL-TR-70-60

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT
This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson AFB, OH

Four papers, each describing a different approach to modelling man, are presented. The first paper describes an extension of the servo theoretic approach to describing the human operator as an active element of a control system. The model presented has been developed to describe and predict muscular actions. The second paper addresses the monte carlo simulation of human performance within a task and time analytic framework, and illustrates the current state-of-the-art. A third paper deals with man-computer interaction in information-processing and decision-making tasks. An attempt was made to describe such interactions in a manner that facilitates the allocation of tasks to man and the computer. The fourth paper demonstrates the feasibility of graphically portraying human biomechanical movements on an IBM 2250 graphic display console. Such techniques can simulate human movements and aid the designer in optimizing workplace geometry. Together, these papers illustrate the breadth of techniques available for modelling man in a man-machine environment. They do not exhaust the spectrum, but are representative. None of the papers attempt to treat or develop a comprehensive concept of man modelling. Instead of reviewing an entire subject area, the papers review in some detail a specific application or an approach to man modelling.

DD FORM 1 NOV 65 1473

Security Classification

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Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Simulation Modelling Decision making Human factors Computer graphics Cockpit layout Task Analysis Human muscular action.						

Security Classification

INTRODUCTION

An attempt will be made to introduce the topics covered by this Panel Session in an effort to provide a historical and conceptual frame of reference.

Models of physical processes are already well developed and widely accepted. Their utility to science and engineering is hardly questioned. Attempts to model or even describe human performance are not as well accepted. It is almost ironic that an attempt to approach human behavior on an objective, rational basis is met with an emotional reaction; but if one remembers history, man's first attempts to model the universe around him were certainly received no better by contemporaries of that day and age.

While an apologetic could be developed, no attempt will be made to provide one here. Models of man are not only interesting in their own right, at least to the model builder; but there have already been enough applications of the models to justify their development.

Organization of the Panel

There appeared to be several approaches to organizing this session. First, one could attempt to enumerate and describe the entire spectrum of approaches suggested for modelling man. These in turn could have been critiqued for their assets and liabilities with recommendations for extending their assets and for overcoming or circumventing the liabilities. An alternate to this would be to describe the chronological development of one or more of the available modelling techniques discussing how concepts emerged or were discovered and explaining the progression of ideas and contributors that have shaped the discipline. A third approach would have been to survey the current and future needs of the design community in an attempt to determine information requirements. From this one might deduce the characteristics models should possess and to what extent current techniques satisfy these demands or what additions and modifications are indicated.

There were two problems with all of these approaches: (1) they were not expedient and would require considerable preparation, and (2) coverage would be superficial in some areas and overwhelming in others. Some modelling techniques, such as the servo theoretic approach (for deriving a describing function of the human operator), have been explored for a number of years, have a rich historical heritage from the physical sciences, and have manifold applications, implications, and complications. On the other extreme, some techniques are only now beginning to emerge, have very sparse historical precedents, and cannot demonstrate any widespread impact because they are still in the development stage. While one or another approach seemed to suit a discussion of some particular modelling technique, it appeared ill suited for others. Consequently, a compromise was suggested.

By allowing selected individuals the freedom to describe their current efforts, it appeared possible to cover several representative applications or approaches to man modelling. One could review the status quo by example and leave details for subsequent literature review. Efforts that are exploratory could be more formally presented though their ultimate impact might be beyond discussion. This appeared to unburden the authors, while simultaneously it provides some organization to the session.

Four approaches to man modelling were selected for discussion: (1) describing functions, (2) monte carlo simulation, (3) decision theoretic paradigms, and (4) representational modelling of biomechanical movement.

Describing Functions

This is the oldest and perhaps classic approach to man modelling in a systems context. Man is treated as a component of a servo control system and is subjected to the same mathematical analysis as a hardware component would be. Interest in this sort of model has increased to the point where advocates convene annually to report on and discuss problems of mutual interest.

In recent years, it has been suggested that this approach is applicable not only to man as an integral functioning component of a system but that the model might also be used to describe the systems which make up the man: his cardiovascular system, the renal-portal system of the kidney, or his neuro-muscular system.

Dr. Apter's paper discusses her work in this area and the success she has had in being able not only to describe muscle functions in generalized fashion but to accurately predict how the neuromuscular system will respond to drugs.

While this specific application may be of only tangential interest to current practitioners of human engineering, this presentation should illustrate two important points: (1) rather elaborate physical models of biological processes can be developed and empirically validated against laboratory data; and (2) the existence of this model allows a prediction of results to new stimuli beyond those which initially helped the builder formulate his model. This is particularly needed in areas where experimental data are wholly lacking, cannot be readily collected, or would involve the creation of unreasonable test environments.

Monte Carlo Simulation

During the development of most systems, a contractor is required to perform a task and time line analysis in support of personnel subsystem considerations. Beyond this immediate requirement to produce data that supports planning, there is a growing interest in stepping beyond this static view of man in the system. One would like to reflect the impact human performance variability and individual differences can have on mission success. Ultimately the ability to simulate this dynamic relationship will lead to the subsequent development of techniques which essentially backsolve the simulation, searching out the contributors to poor mission performance and hopefully suggesting areas where additional human engineering could enhance system performance. Dr. Wolf discusses an existing operator simulation model which has already been used during systems development and has experienced almost constant development, enrichment, and adaptation to new users or applications. This model has been validated in several ways in different applications. It provides a workable and powerful tool for the human engineer, but it also provides a tool for those engaged in research.

This past year the model was modified to operate in parallel with an ongoing experiment. Tasks readily simulated by the model can be executed, passing on to the experimenter and/or subject the results of this simulated task sequence. The subject in turn would then complete a series of tasks, and his performance would be measured and accumulated. After several iterations or trials, sufficient data should be acquired to permit simulation of the entire sequence. This technique is designed to aid the researcher in validating selected parameters of the model and to collect data for tasks where the input required for simulation is either not available or of questionable accuracy.

Decision Theoretic Paradigms

In addition to the work completed by the now disbanded Decision Sciences Laboratory, the Aerospace Medical Research Laboratory also sponsored research on multi-man and computer systems for information processing and decision making. Until two years ago, this research was conducted at Ohio State University in the Aviation Psychology Laboratory. Dr. Schrenk was one of a team of research psychologists involved in these studies.

While there are normative models of decision making which are based on assumptions of the "rational" man, and there are descriptive models of the human as an information processor, there is no composite model of the information gathering and decision making activities of a large multi-man and machine system. In effect, designers of such systems receive all too little guidance from human engineers. Our principal efforts have concentrated on controls and displays, and relatively little attention has been given to the human engineering of man-computer interaction.

There has been a good deal said about the need to study this relationship, and there have been numerous attempts to perform related research studies. The only difficulty is that this research has been accomplished in something of piecemeal fashion for lack of a unifying framework. In effect, the researcher and scientist is still in the process of trying to structure the problem and make it more amenable to discussion as well as research.

Dr. Schrenk has attempted to construct a preliminary version of a paradigm or unifying framework. While it should be of interest to those engaged in research on information processing and decision making, it should also be of interest to the designer as well. It presents a theoretical context in which one can at least pose the question: "What shall the machine do, and which tasks are better allocated to man?" This has been of concern to human engineers since the inception of the profession.

Representational Modelling of Biomechanical Movement

"A picture is worth a thousand words" may be a tired and worn cliche, but it is difficult to refute the basic assertion behind such a pronouncement. Cockpit geometry and workplace layout problems are among the oldest concerns of the profession, and they reappear with the design of any new system. Mock-ups and actual demonstration exercises have often been resorted to as a final test of a proposed panel layout. Maintainability demonstration requirements are now part of contracts for new systems.

The ability of the computer to simulate all sorts of models has been impressive for certain kinds of design analysis, but far more impressive are the capabilities that can be realized by using computer graphics. One of the more exciting notions is to consider the graphic display of human movement in given workplace configuration.

Imagine your being able to watch a 5th percentile pilot perform a nominal mission and to have the capability of changing the pilot to 95th percentile observing how these pilots perform by watching a computer-driven display. Among the implications beyond this simply anthropometric example are those dealing with questions of visibility outside the cockpit, accessibility of components for scheduled and unscheduled maintenance, studying the impact that changes in workload might have on the economy of movement, and so forth. The possibilities have scarcely been enumerated.

Mr. Ryan has been working under JANAIR sponsorship for several years now and has developed prototype routines for both two and three dimensional representations of biomechanical movement. While there is much work yet to be done, it is impressive how much has already been accomplished.

A Model for Muscular Contractile Elements Suitable for Quantifying Human Muscular Action *

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ABSTRACT

A self-consistent model based on valid physical and chemical laws known to govern the visco-elastic behavior of polymeric materials was developed to be also consistent with muscular behavior. Exposure of the model to various perturbations like stretch, loading, chemical reactions or diffusion of ions replicated events known to take place during stretch, loading and stimulation of muscle, whether smooth or striated. The equations of motion of the model so perturbed were solved with an analog computer which generated stress, strain and strain rate curves for the model. These curves closely resembled real shortening velocity-time curves, force-velocity curves, isometric tension development and other muscular responses. Therefore it was possible to obtain initial estimates of model parameters from real muscular behavior. These results call attention to some details of real muscular behavior previously not appreciated, like phase gain-angle and elastic modulus enhancement at critical sinusoidal strain frequencies. The general nature of the model makes it possible to formalize more complex perturbations and to quantify a wide range of muscular behavior in a more useful and reproducible way than before.

INTRODUCTION

For the past 3 decades, analysis of the behavior of muscles has been simplified with models combining one or two "contractile elements" with one or more springs as did Hill (1938), Parmley and Sonnenblick (1967), and Bahler (1968) (Figure 1). The behavior of contractile elements is generally formalized as an equation relating empirically-determined muscle-shortening velocities, v, to forces F opposing the shortening. Whether the empirical data came from excised muscle or muscle in situ, and whether terminal velocities or peak velocities were used, the force-velocity relationship has seemed to be hyperbolic; that is, of the form

$$F = \frac{a}{v + b}. \tag{1}$$

Recently Vickers and Sheridan (1968) pointed out that models incorporating only springs with a Hill contractile element were inadequate to match muscular behavior at various stimulus levels. Therefore, they replaced one spring by a dashpot whose viscosity depended on stimulus levels. This was the first important change in muscle models in the past 3 decades.

In the present paper we propose a still broader generalization by expressing both the Hill contractile element and the Vickers and Sheridan

* Supported in part by USPHS grants GM-14659, HE-05808 and CA-06475

dashpot in terms of molecular events in muscle. These changes seem indicated since, although the Hill contractile element has been conceptually useful, it does not predict many of the important characteristics of muscle behavior without additional hypotheses. Some examples are the detailed time course of muscular shortening during contraction against a load (Wilkie, 1949), isometric tension development during stimulation (Bahler, 1968; Buller and Lewis, 1965), the existence of a phase gain-angle between stress and strain at certain oscillatory strain frequencies (Apter and Marquez, 1968a, Apter and Marquez, 1968b; Ruegg, 1968), elastic modulus enhancement (Apter and Graessley, 1968), and variability of force-velocity curves with muscular damping characteristics (Vickers and Sheridan, 1968) (Figure 2).

This limitation of the hyperbolic relation is not surprising since it indicated only that muscle, in certain special circumstances, behaves approximately like a constant power device. There is no reason for expecting the relationship, _per se_, to permit predictions about the general behavior of muscle. What is needed is a "contractile element" whose properties are derived from the physical and chemical changes underlying muscular contraction. The response to any feasible forcing could then be predicted. The present study develops a model for this purpose. Experimental data can be used to obtain numerical values for the model parameters, thereby quantifying real behavior.

METHODS

The physical laws used to develop the model are: (1) in a spring, stress σ is proportional to strain ε and the constant of proportionality is E. (2) in a dashpot, stress is proportional to strain rate $\dot{\varepsilon}$ and the constant of proportionality is η; (3) in a three-parameter viscoelastic solid E_1, E_2 and η can be obtained from stress relaxation curves using peak tension, steady state tension and the time to go from peak to steady state; (4) the values for E_1, E_2, η and the rest length depend on the arrangement of the macromolecules in the system; and (5) the macromolecular arrangement in turn may be influenced by substances or "impurities" whose entry rates into the polymer depend to some extent on strain and strain rate (Tobolsky, 1960).

MODEL FOR A CONTRACTILE ELEMENT

A three-parameter viscoelastic model was chosen because the stress-relaxation of muscle can be represented by no simpler body (Apter, Rabinowitz and Cummings, 1966). The mechanical response of the model is represented by the following equation (Kolsky, 1962)

$$\sigma + \frac{\eta}{E_2}\dot{\sigma} = E_1 \varepsilon + (E_1 + E_2)\frac{\eta}{E_2}\dot{\ell} \tag{2}$$

where σ is stress and ε is strain, defined as

$$\varepsilon = \frac{\ell - \ell_o}{\ell_o} \tag{3}$$

with ℓ being the existing length and ℓ_0 the instantaneous rest length of the muscle.

Let us assume that, whatever the stimulus, muscle changes its contraction level because of the level of some substance, N, in the cell. Let us also say that the concentration, n, of N varies with time, t, as governed by

$$\dot{n} = k_2\varepsilon - k_3 n + S(t) \qquad (4)$$

The term on the left is the time rate of change of n within the cell. The first term on the right corresponds to a diffusion of N into the cell at a rate proportional to the strain. The second term corresponds to deactivation or removal of N from within the cell at a rate proportional to its concentration. The third term represents the addition of N to the cell through stimulation. Suppose stimulation begins at time t_0 and continues more or less constantly until t_1. For this case we have chosen the following simple form for S(t);

$$\begin{aligned} S(t) &= 0 && 0 < t < t_0 \\ &= k_7 && t_0 < t < t_1 \qquad (5) \\ &= 0 && t_1 < t < \infty \end{aligned}$$

in which k_7 is a constant. Thus, stimulation corresponds to a constant rate of admittance of N to the cell during the period of stimulation.

The instantaneous rest length and the viscoelastic parameters of muscle are taken to be the following simple functions of concentration n.

$$\ell_0 = \ell_0^\infty + \frac{\ell_0^\circ - \ell_0^\infty}{1 + k_1 n} \qquad (6)$$

$$E_1 = E_1^\infty - \frac{E_1^\infty - E_1^\circ}{1 + k_4 n} \qquad (7)$$

$$E_2 = E_2^\infty - \frac{E_2^\infty - E_2^\circ}{1 + k_5 n} \qquad (8)$$

$$\eta = \eta^\infty - \frac{\eta^\infty - \eta^\circ}{1 + k_6 n} \qquad (9)$$

with the superscripts $^\circ$ and $^\infty$ referring to completely relaxed (n =0) and completely contracted ($n = \infty$) values respectively. Thus the moduli and viscosity increase with n and the rest length decreases, which is consistent with known behavior in contraction (Ramsey and Street, 1940; Apter et al., 1966).

All these equations have specific physical and physiological counterparts. The physical counterparts of equation (2) are illustrated in Figure 3. Mathematically equation (2) is equivalent to either a Maxwell element in parallel with a spring or a Voigt element in series with a spring

They are generalized representations of experimental data on viscoelastic responses of excised muscle (Apter et al., 1966). Inertial terms have been omitted to keep the analysis simple. In general, it is possible to design real experiments to minimize inertial contributions, or to account for them on an ad hoc basis.

In our view equation (4) represents a highly simplified description of the events known as excitation-contraction coupling (Sandow, 1965). This equation is probably the simplest formalism consistent with actual events: ions such as K^+, Na^+ and Ca^{++} enter the muscle cell through its membranes during stimulation or enter through membrane "pores" created or enlarged when the muscle is stretched. The removal term could be binding of ions by sarcoplasmic reticulum or exit of ions by pumping through the cell membrane. Equations (6) to (9) incorporate the events known as the "sliding filament hypothesis" of muscular contraction (Huxley, 1963). The rearrangement of actin and myosin that takes place as muscle shortens (or as ℓ_0 decreases) are assumed here also to be associated with increases in E_1, E_2 and η_0. Their interrelation is shown in Figure 4.

Undoubtedly, the precise role of ions in excitation-coupling, and the relation between overlap of actin and myosin and the density of cross-links, will become clearer as more work is done. It does not seem necessary, however, to wait for more definitive results to develop a model for the contractile element, provided of course that the empirical nature of equations (6) to (9) is recognized, and that refinements and modifications may become necessary as more is learned.

This model represents the elastic (or energy-conserving) properties of materials as springs and the viscous (or energy-dissipating) properties as dashpots since muscle, whatever its level of contraction, is a viscoelastic material. The unique energy-producing characteristic of muscle has been embodied in springs and dashpots whose parameters depend on the level of some chemical in the environs of the springs and dashpots. In other words, muscular contraction is represented not by "force generators" or "internal loads," (Bahler, 1968) but by variations in spring constants, dashpot viscosities and their unstressed lengths.

How this system is able to do mechanical work is best seen by an example. Consider a muscle initially stretched from $\overset{\circ}{\ell}_0$ to ℓ by some external agency, and held at ℓ until the stress becomes constant. The rest length drops from $\overset{\circ}{\ell}_0$ to ℓ_0 as N builds up in the muscle. Eventually the concentration of N levels off at a value appropriate to the empirical static strain ε. Now superimpose a small oscillatory strain. As the strain rises, work is being done by the external agency on the muscle. The component N diffuses into the muscle, increasing E_1, E_2 and η and decreasing ℓ_0. The stress rises accordingly. When the strain reaches its maximum the stress continues to grow as N continues to enter the muscle. As ε now decreases, the muscle does work on the external agency. The flow of energy is greater now than in the rising part of the cycle because now the concentration of N is greater, making ℓ_0 smaller and the stress greater.

Clearly the generation of power depends on frequency in oscillatory situations. If oscillations are sufficiently slow the concentration of N will be in step with the strain and the muscle will be dissipative because of its viscosity term. Likewise, at sufficiently high frequencies the concentration of N will be unable to respond to the changes in strain and no net energy will be produced. Only at some intermediate range of frequencies will a substantial phase lag appear. In this range the muscle will produce mechanical energy.

EXAMINATION OF THE MODEL

The behavior of the model was examined with an analog computer. A variety of forcings were imposed, all of which have been used in experiments on muscle: step function stretch, oscillating strain, stimulation of a loaded muscle free to shorten, and stimulation at fixed length (isometric). Values for the moduli, the viscosity, and the rest length were taken directly from experimental stress-relaxation studies on smooth, striated and cardiac muscle (Ramsey and Street, 1940; Sonnenblick, 1965; Apter et al., 1966).

Various values of the k_i ($i = 1,.,.,.,7$) were tested to find combinations which would simulate real muscular behavior. The absolute values of $\hat{n}$, k_2 and k_3 in equation (4) did not appear to be contributory so long as the necessary scaling factors were used. When $k_2/k_3 = 0$ and $k_7 = 0$, the concentration of N remains zero and the model behaves like an ordinary linear viscoelastic solid. When $0 < k_2/k_3 < 1.5$ and when $k_1 = k_4 = k_5 = k_6$ and in the range 0.3 to 1.0, the model behaves like in vitro smooth muscle in the absence of its usual chemical mediators for contraction (relaxed smooth muscle). With the same range of values for k_1, k_4, k_5, and k_6 but $1.5 < k_2/k_3 < 3.5$, the model behaves like smooth muscle in the presence of neosynephrine or other chemical mediators (contracted smooth muscle). If $3.5 \leq k_2/k_3 \leq 7.5$, $k_4/k_1 = 2$, and $k_1 = k_5 = k_6 = 1$, the model behaves like striated muscle. Stimulation was simulated by letting n rise very fast, $0 < k_7 < 100$ with the muscle held at fixed length only during the stimulus and then released to generated velocity-time curves (Figure 7) or force-velocity curves (Figure 8). Stimulation also was imposed at several frequencies with the muscle maintained at fixed length to give isometric tension development curves (Figure 10).

In general, the model was successful in simulating every published aspect of real muscular behavior. The model responses are in Figures 6-12 and some real responses are in Figure 2.

DISCUSSION

This new model for a contractile element of muscle calls attention to and emphasizes the remarkable similarity in behavior among several types of muscles. For example, striated muscles were assumed to behave entirely differently from smooth muscles which in turn were presumed to differ from each other (Gelfan, 1960). The present studies show that the same model can account for the behavior of all these muscles, provided only that the

sensitivity of the viscoelastic parameters to the effects of some environmental substance, N, is characteristic (striated muscle having large values of k_i ($i = 1,4,5,6$); smooth muscle having small values) or that the response time is characteristic (striated muscle having a larger k_2/k_3 than smooth muscles). It is important to note that the same ranges of k_i values satisfy all observations on each kind of muscle. Thus, for striated muscle the isometric tension development; similarly for relaxed and for contracted smooth muscle.

This consistent match of k_i values with a particular kind of muscular behavior makes the model highly attractive and useful. What is more, since the reactions postulated in the model may also occur, although very slowly, in all polymeric systems (Tobolsky, 1960), we conclude that muscle behaves like any viscoelastic material, unique primarily in undergoing the chemical changes associated with contraction and relaxation very rapidly. Thus, there is no need to hypothesize empirical energy generators; a model which simply mediates, through a response to chemical changes in the environment, in the conversion of chemical energy into mechanical energy, can behave in all known mechanical respects like real muscle.

This model suggests new ways to analyze data already published on limb movements and also suggests some experiments not yet performed. A revised data analysis has already been attempted successfully by Vickers and Sheridan (21) with their model already referred to. Since the data they analyzed were formalized via a describing function, it would not be valid without further experiments to extend the analysis to include the system response to forcings of a generalized nature. It is necessary, therefore, in any case to perform new experiments on human limbs. The present model would use experiments correlating stress, strain and strain rate to obtain numerical values for muscular parameters of this model in response to some simple forcing like a suddenly imposed movement from one position to another. Since the model is a self-consistent entity, these parameters could be used to analyze the behavior of human limbs in response to any other kind of forcing, like a vibration, oscillation, or ramp function. It would not be necessary to restrict all experiments to the kind used to obtain the parameters.

The study calls for instrumentation capable of monitoring limb movements and accompanying stresses. Such instrumentation has been developed by Cornell Aeronautical Laboratories and promises to provide data suitable for estimating the values of the parameters of the present model. For example, a force of known magnitude could stretch a muscle, as in producing the knee or ankle jerk reflex. If nerve transmission were intact, one set of muscles would be stimulated to contract, the antagonists would be inhibited to relax. Therefore, the model would have to be extended to an agonist--antagonist pair, using the method suggested by Vickers and Sheridan to define the mechanics of the limb motion. Both groups of muscles would be started at a set of initial conditions $\sigma(0)$, $\varepsilon(0)$ and $n(0)$; --all amenable to estimate or to determination as parameters.

The stimulus to contraction and relaxation could be formalized as the

sudden rise or drop in η of equation (4); this change being induced by repetitive bombardment of the muscle by nerve pulses of a determinable frequency. The force, stress rate, strain and strain rate at the end of the limb could easily be monitored to provide these variables σ, $\dot{\sigma}$, ε and $\dot{\varepsilon}$ to the equations of the model. There remain E_1, E_2, η and the k_i ($i = 1, 2, \ldots 6$) as parameters to be determined. This is not so formidable a task as you might think. Methods successfully used by Taylor and Brown (19) to determine molecular orbitals have also been used successfully by Wilson et al. (23) to determine renal system parameters of a model similar to the one here proposed.

The computer program which would use experimental data to determine the constants for this model consists of three parts (23): (1) the main program which pre- and postprocesses the data and results, and which invokes a general-purpose nonlinear estimation program; (2) the nonlinear estimation program; and (3) a set of subroutines, appropriate to the model, which solve the various differential equations and which compute the values of various functions and derivatives which are required by the nonlinear estimation program. It was necessary to make initial estimates of all parameters and these were made by analyzing stress-relaxation curves.

The main program, before invoking the nonlinear estimation program, reads the following input information; identification for the particular set of data, parameters associated with the set of data, the data themselves, the boundary conditions, the values for $\sigma(0)$, $\varepsilon(0)$ and $\eta(0)$, a set of values of t for which E_1, E_2, η and the k_i are to be calculated from the final values of the determined constants, and lastly, initial estimates for the constants. The main program invokes the nonlinear estimation program. After obtaining the final values of the constants from the nonlinear estimation program, the main program outputs calculated values for E_1, E_2, η and the k_i using these constants, for the values of time specified earlier. Also outputed is the final value of the rms errors, defined to be the square root of the sum of the weighting factors w_i times the squares of the differences between the estimated and calculated values of

$$\text{rms} = [\Sigma\, w_i (C_{calc} - C_{obs})^2]^{1/2}$$

The weighting factors were all unity in this case because of the analogue nature of the data.

Given a model with unknown constants and a set of initial estimates for these constants, the nonlinear estimation program seeks to obtain a solution (a set of values for the unknown constants) which minimizes the rms error as defined above. This is, of course, a local minimum for a region of space which is determined by the initial estimates for the constants. The information about the model is communicated to this program by a set of subroutines whose purpose is to supply calculated values of E_1, E_2, η and the k_i, and the derivatives of these quantities with respect to the unknown constants.

Experiments providing a quantified response of an agonist-antagonist

pair are now being performed to evaluate the effects of tranquillizer drugs on neuromuscular function. We also plan to study the responses of handicapped personnel to environmental stress. This model seems to be more widely useful than a transfer function or a describing function formalism and I hope it will be considered worthy of widespread testing.

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Appendix

In order to obtain a rigorous expression for the relation between veolcity of shortening, $\dot{\ell}$, and load on the model, start with equation (1), using Equation (2) and remembering that $\dot{\sigma} = 0$ and $\sigma = \sigma_0$ to reproduce experiments of Fenn and Marsh (1935). Then have

$$\sigma_0 = E_1 \frac{\ell - \ell_0}{\ell_0} + (E_1 + E_2) \frac{E_2}{\eta} \dot{\ell} \qquad \text{(i)}$$

Solve for $\dot{\ell}$:

$$\dot{\ell} = \frac{\eta}{(E_1 + E_2)E_2} \quad \sigma_0 - E_1 \frac{\ell - \ell_0}{\ell_0} \qquad \text{(ii)}$$

Take the next time derivative of (ii) and keep in mind that η, E_1, E_2 and ℓ_0 are all functions of time because of equations (3) and (6) to (9). Thus

$$\ddot{\ell} = \frac{E_2(E_1 + E_2)\dot{\eta} - \eta[\dot{E}_1E_2 + 2E_2\dot{E}_2 + E_1\dot{E}_2]}{E_2^{\,2}\ (E_1 + E_2)^2} \quad \sigma_0 - E_1 \frac{\ell - \ell_0}{\ell_0}$$

$$- \frac{\eta}{E_2(E_1 + E_2)} \quad \dot{E}_1 \frac{\ell - \ell_0}{\ell_0} + E_1 \frac{\dot{\ell}\ell_0 - \dot{\ell}_0\ell}{\ell_0^{\,2}}. \qquad \text{(iii)}$$

Find the maximal shortening velocity $\dot{\ell}^*$ by setting (iii) equal to zero and solve for $\dot{\ell}^*$. This is

$$\dot{\ell}^* = \ell_0 \quad \frac{E_2(E_1 + E_2)\dot{\eta} - \eta[\dot{E}_1E_2 + 2E_2\dot{E}_2 + E_1\dot{E}_2]}{E_1E_2(E_1 + E_2)\eta} \quad \sigma_0 - E_1 \frac{\ell - \ell_0}{\ell_0}$$

$$+ \frac{\dot{E}_1(\ell - \ell_0)}{E_1} \quad \frac{\ell\dot{\ell}_0}{\ell_0} \qquad \text{(iv)}$$

If E_1 is high, then it is large in comparison with E_2 and $\dot{E}_1$ is small.

Therefore the coefficient of $\sigma_0 - E_1 \dfrac{\ell - \ell_0}{\ell_0}$ is also small, so that, for high

$$\dot{\ell}^* \approx \frac{\ell\dot{\ell}_0}{\ell_0} \qquad \text{(v)}$$

so that $\dot{\ell}^*$ is not a strong function of σ_0 if E_1 is high. This is in keeping with the computer output summarized in Figure 9. If E_2 is high, it becomes nearly equal to E_1 and

$$\dot{\ell}^* \approx - \dot{E}_1 \quad \frac{(\ell - \ell_0)}{E_1} - \frac{\ell\dot{\ell}_0}{\ell_0} \qquad \text{(vi)}$$

so that, again $\dot{\ell}^*$ changes only slightly with σ_0, again in keeping with the computer output.

On the other hand, if η is high and $\dot{\eta}$ is therefore small, $\dot{\ell}^*$ is a strong function of σ_0 as the computer output suggests.

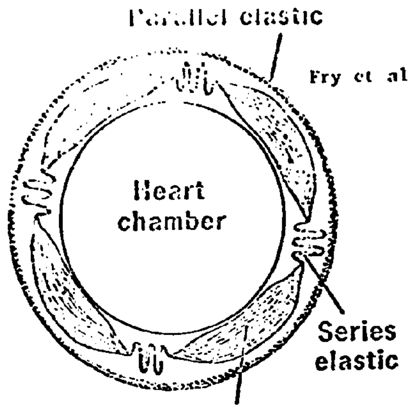


FIGURE 1
Mathematical model of heart according to A. V. Hill's skeletal muscle model.

Fry et al, 1964

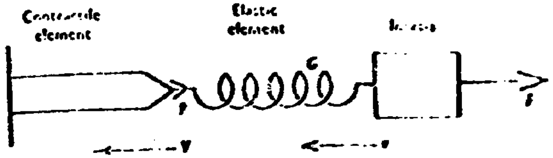


Fig. 6. Proposed structure of ...

Willkie, 1949

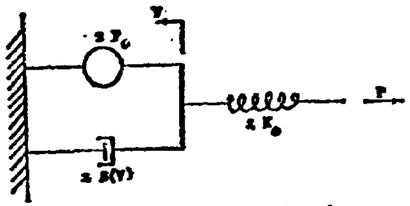


Fig. 2. Schematic model of a single muscle.

Vickers and Sheridan, 1968

BAHLER: MODELING OF MAMMALIAN SKELETAL MUSCLE

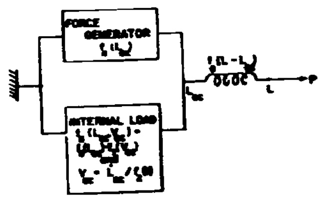
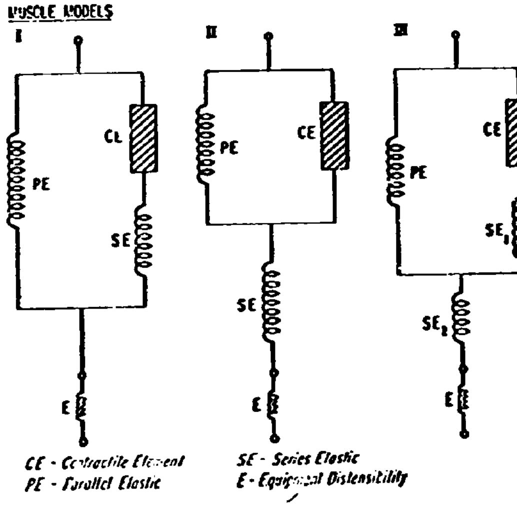


Fig. 9. Composite model of mammalian skeletal muscle. Parallel elastic element has been neglected. L_{ce} length of contractile element; L length of muscle; P external load.

Bahler, 1968

Bahler, 1968



CE - Contractile Element
PE - Parallel Elastic
SE - Series Elastic
E - Empirical Distensibility

FIGURE 6

Parmley & Sonnenblick, 1967

Figure 1
Resumé of models for muscles. All include "contractile elements" described by empirical equation fitting.

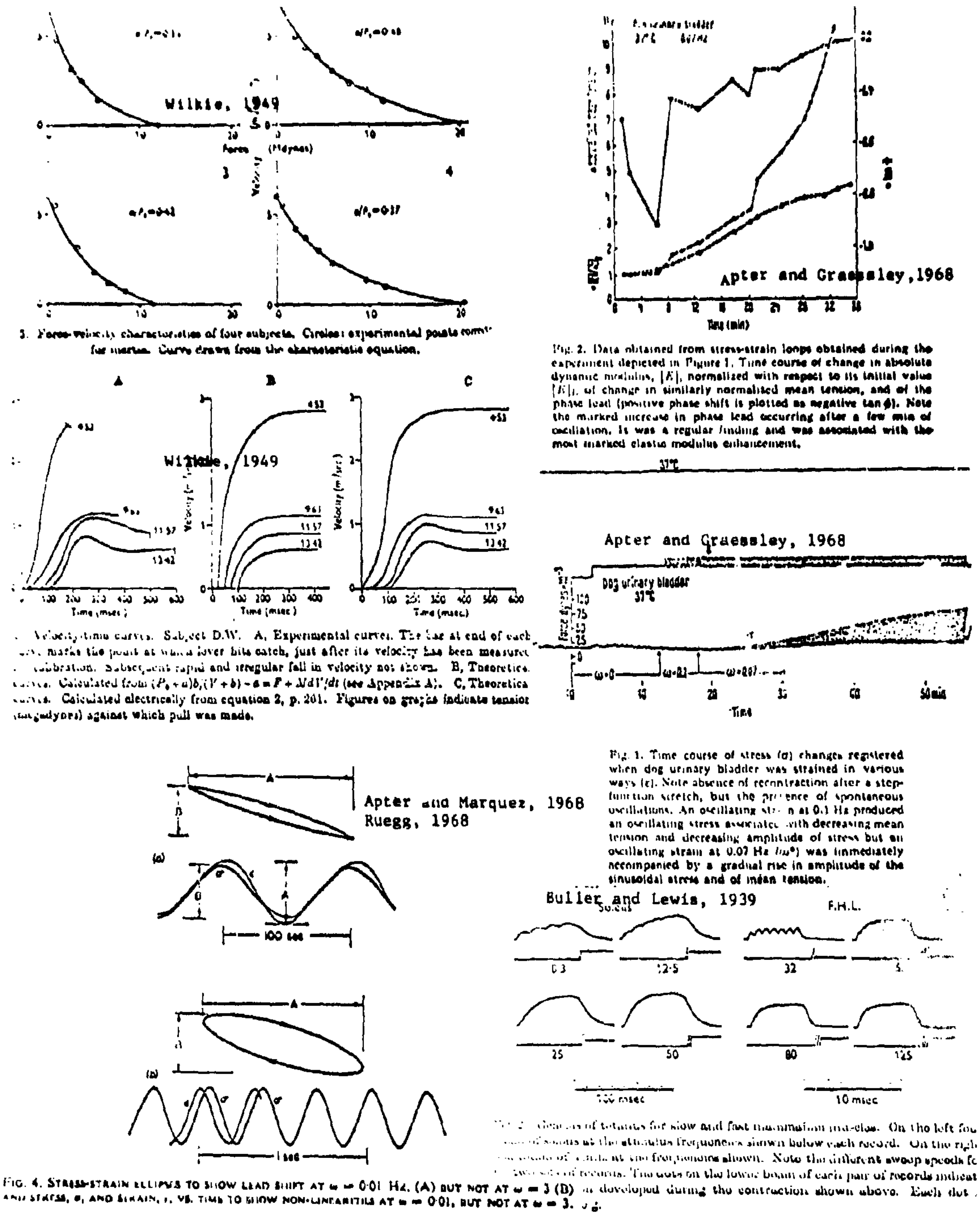


Figure 2 Resumé of known behavior of various kinds of muscles. Hill's contractile element predicts only the force-velocity curves of Willkie, 1949.

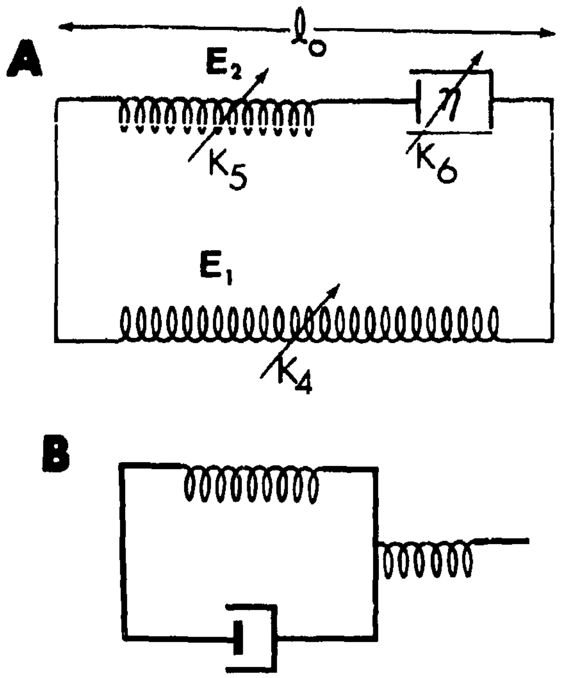


Figure 3
Two models for a contractile element. They are entirely analagous models since they are both described by the same differential equation of motion (equation 2). A is Maxwell model; B is Voigt model.

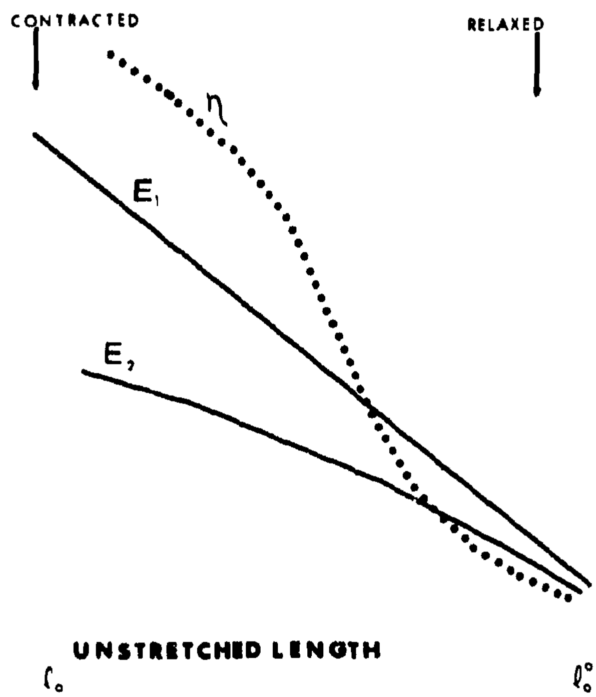


Figure 4.
Data obtained from tables already published for muscle (Ramsey and Street, 1940; Apter et al, 1966.)

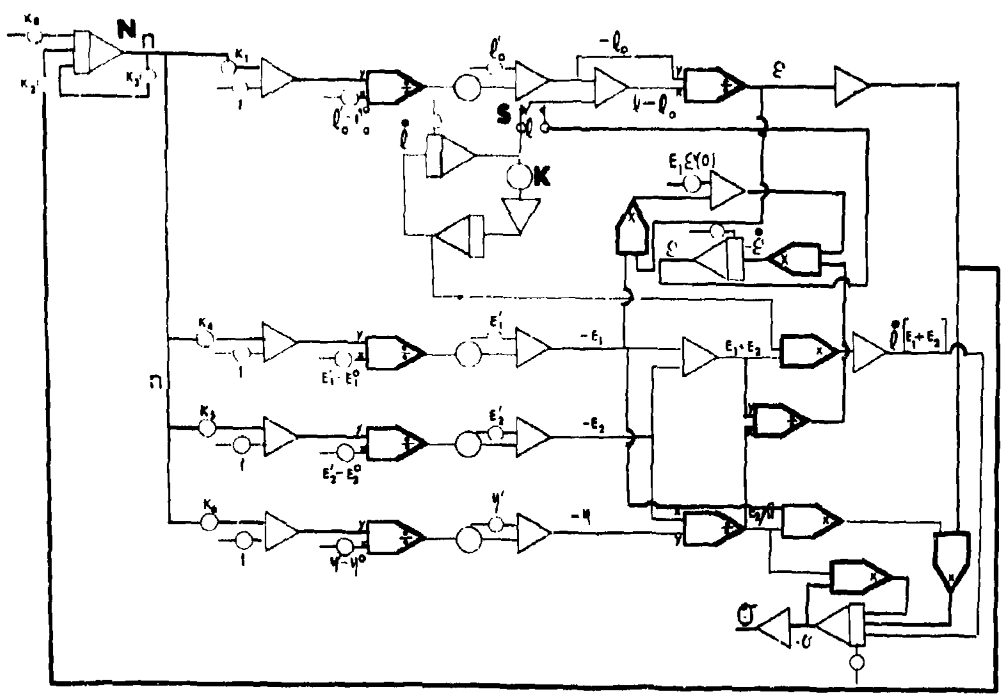


Figure 5

Analog computer program used with suitable scaling factors, to solve equation (1), (2), and (6) to (9). An increase in n to simulate stimulation was added at position N; a step-function strain was imposed at position S. In both instances K = 0. For an oscillating strain, K was varied to vary frequency and N = S = 0. Velocity was ℓ obtained from equations in Appendix. Loading was accomplished at F by keeping $\sigma(0) = E_1\varepsilon(0)$ consistent with E_1 and $\varepsilon(0)$ elsewhere in the program.

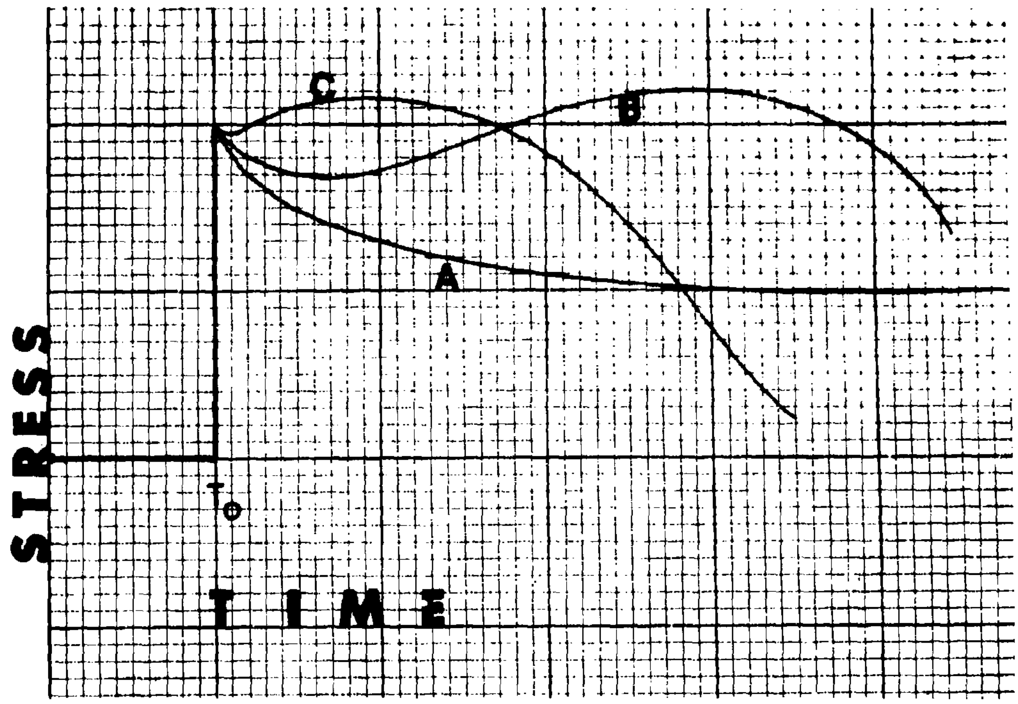


Figure 6.
The responses of model to a step-function increase in length from ℓ_1 to $\ell_2 > \ell_1$ at $t = t_o$. Response A resembles relaxed smooth muscle, Apter and Graessley (in press); response B resembles contracted smooth muscle, Apter and Graessley (in press), and response C resembles cardiac papillary muscle.

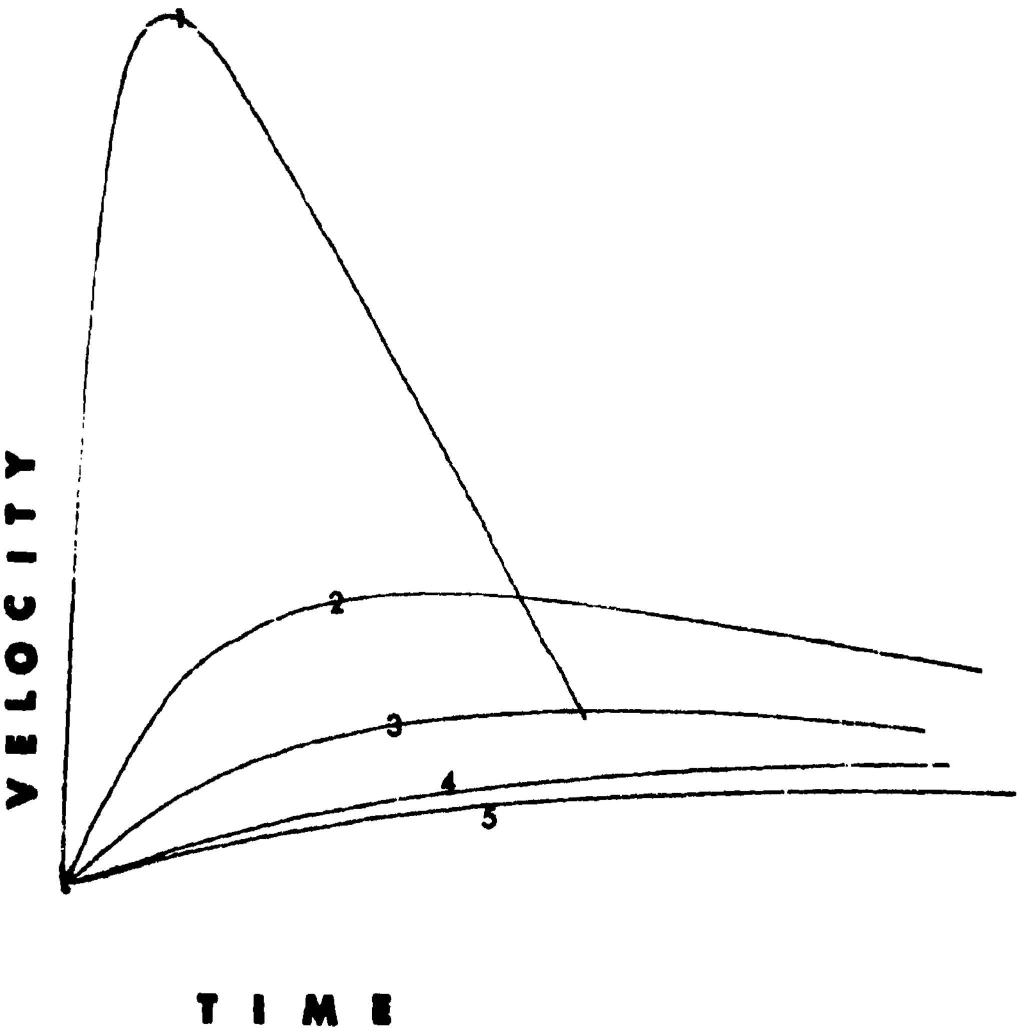


Figure 7
Time course of velocity, $\dot{\ell}$. It shows a maximum which occurs later as σ increases. The numbers on curves give actual σ values in dynes cm^{-2}. It was necessary to find a set of k_i (i = 1...6) such that $\sigma = E_1' \frac{\ell - \ell_0'}{\ell_0'}$ as well as $\sigma = E_1^\circ \frac{\ell - \ell_0^\circ}{\ell_0}$ at the end and the beginning of the shortening process. Otherwise, the relation $\dot{\ell} = \frac{\ell \dot{\ell}_0}{\ell_0} - \frac{\eta}{E_2(E_1 + E_2)} \dot{\sigma} - E_1 \frac{\ell - \ell_0}{\ell_0}$ holds, with E_1, E_2, η and ℓ_0 regulated by equations (6) to (9).

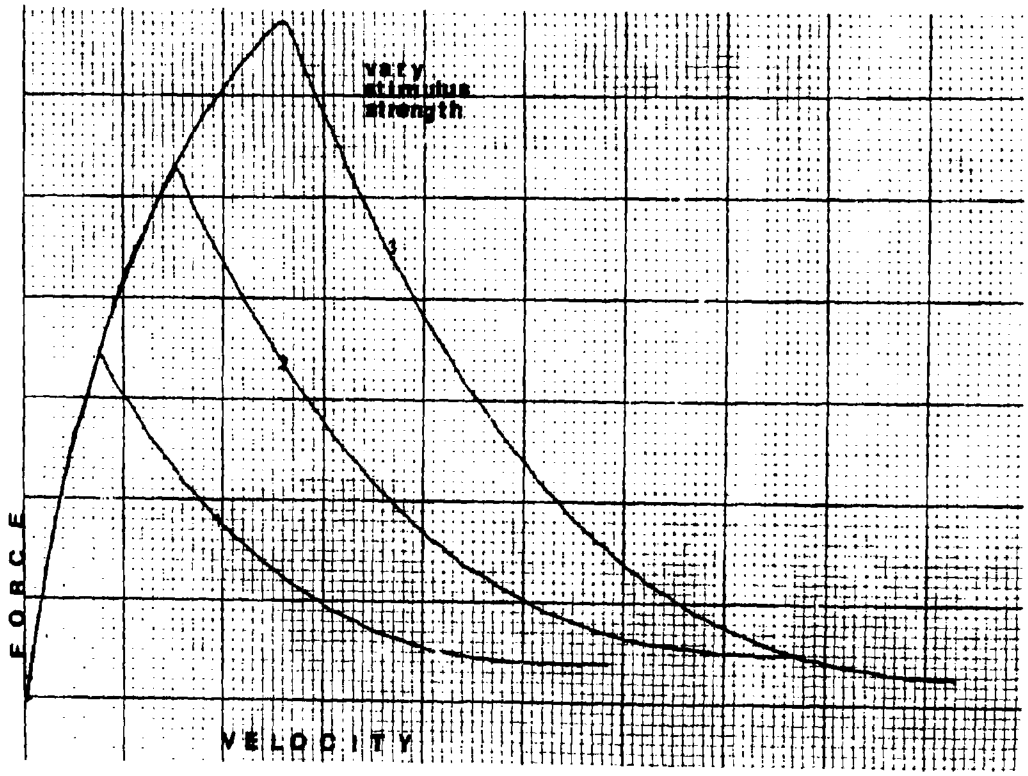


Figure 8
Three force-velocity curves taken at three stimulus levels, quantified simply by the level to which n was permitted to rise as a result on input at N in Figure 5. Here n increased to the point where the force started to drop; then n input was stopped. Force rose, then fell as velocity increased.

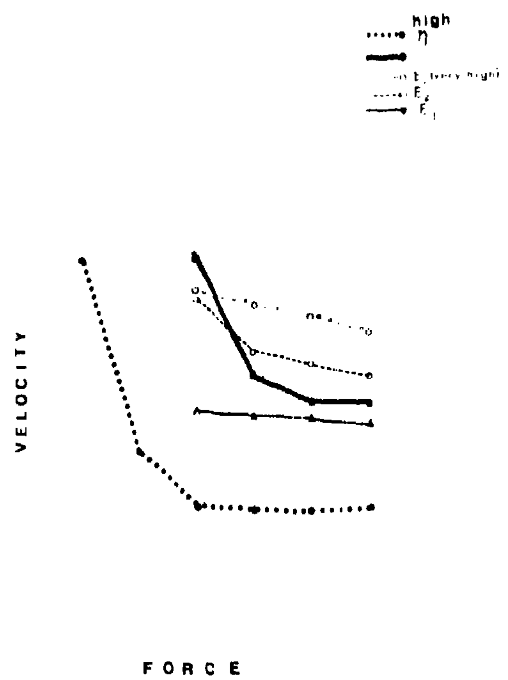


Figure 9

Force-velocity curves using peak velocity of shortening. Shows effect of high E_1, E_2 and η. Not all relationships are hyperbolic as might be expected from analysis set forth in Appendix.

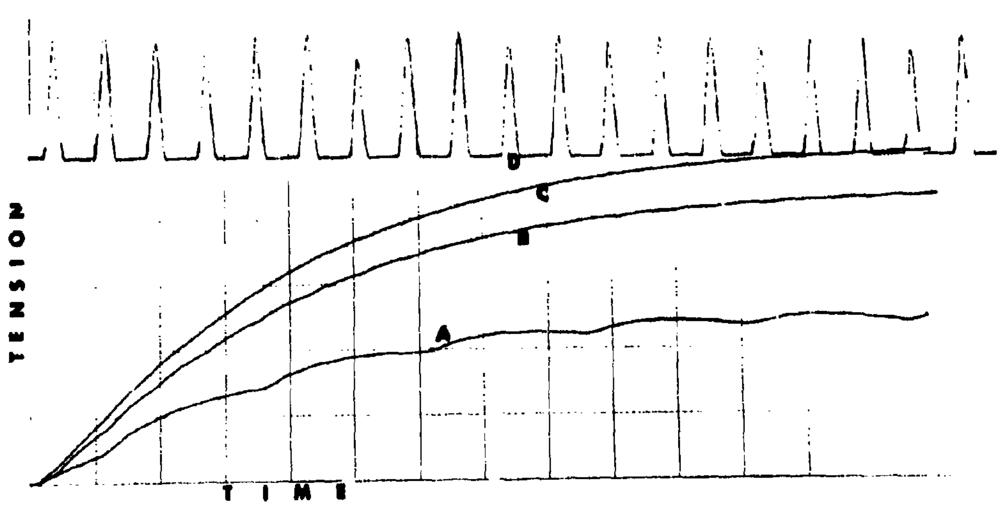


Figure 10

Response of model to repetitive stimulation at constant length and at three frequencies. At low frequency (A) the rise in tension is slow, periodic and reaches a level lower than that at higher frequency (B) and still higher (c). D is n(t) for curve B. All curves resemble data of Buller and Lewis (1965).

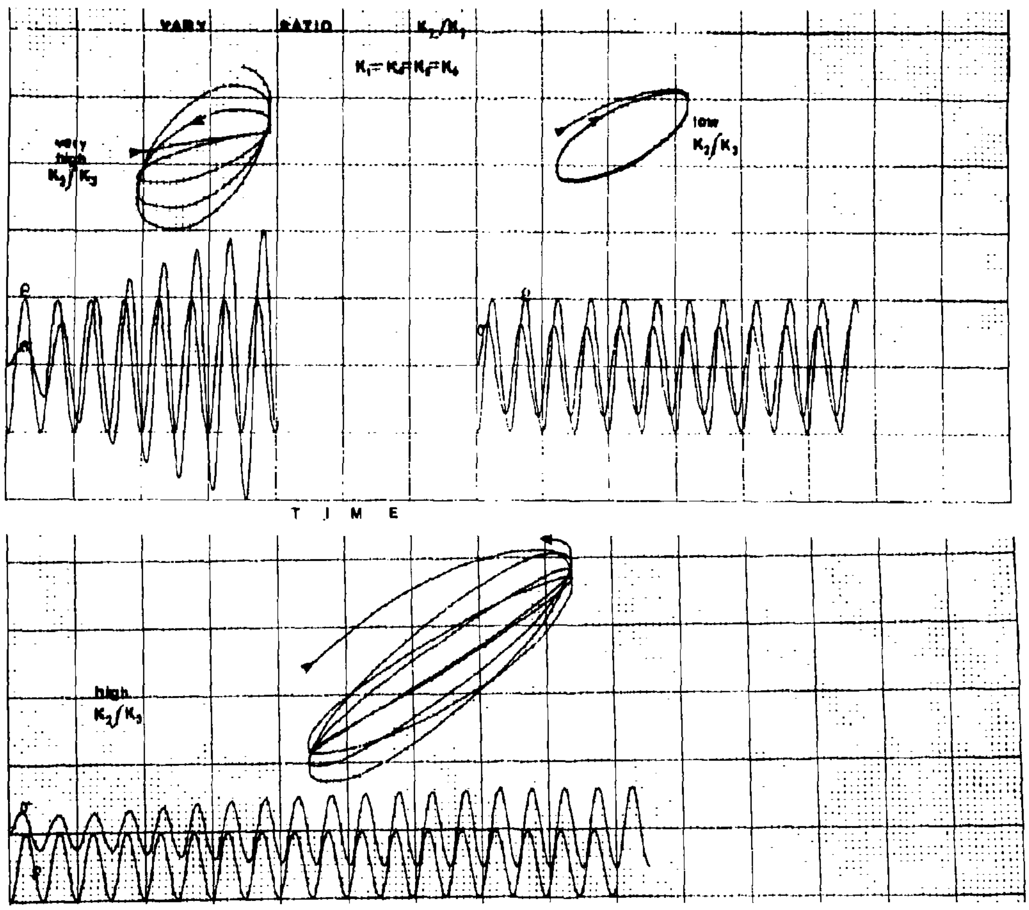


Figure 11

Sinusoidal input (ε) and output (σ) as functions of time (b) and as functions of each other (A) at three levels of k_2/k_3.

I. shows the phase gain-angle and modulus enhancement of $k_2/k_3 = 6$. Enhancement appears as increasing amplitude of σ.

II shows the phase loss-angle and constant modulus of $k_2/k_3 = 0$.

III shows the phase loss-angle and constant modulus reverting to phase gain angle and modulus enhancement of $k_2/k_3 - 3$.

Phase loss means that σ occurs at an earlier time than ε; phase gain is vice versa.

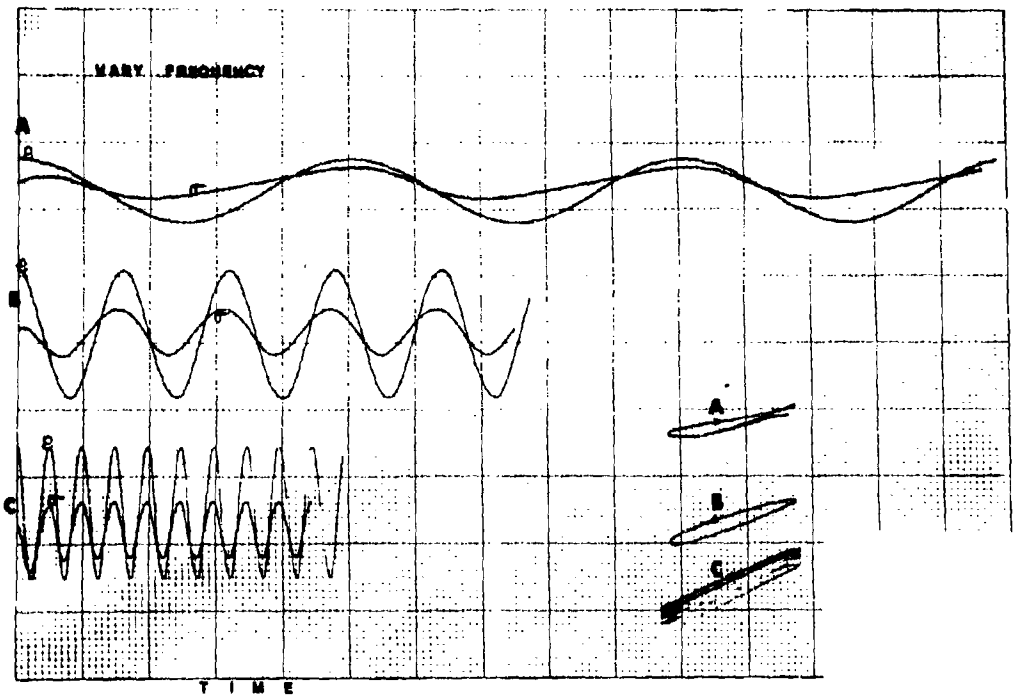


Figure 12

Sinusoidal input (ε) and output (σ) as functions of time (I) and as functions of each other (II) at three frequency levels.

A shows the marked non-linear response with a phase gain at f = .01 Hz

B shows the linear response with a phase loss at f = .033 Hz.

C shows the linear response with a small phase loss at f = .1 Hz.

Computer-Aided Decision Making In Man-Machine Systems

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ABSTRACT

Decision making is often the most complex task which operators of man-machine systems are called upon to perform. The increased use of digital computers in advanced systems increases the possibility of creating information overload situations, but also provides greater potential for aiding decision makers. Unfortunately, despite some very significant research in recent years, there is a scarcity of guidelines for designing system decision functions. This paper briefly reviews some recent research on computer-aided decision making. A conceptual model of an idealized decision process is also presented. The major purpose of this model, which must be considered highly tentative, is to provide a guide to system designers in structuring decision processes. The model also provides a framework for classifying and integrating knowledge about decision behavior.

REQUIREMENTS FOR A DECISION-PROCESS MODEL

During the past decade there has been rapid growth in the use of digital computers in real-time man-machine systems. This trend may be expected to accelerate with the decreasing cost of computers and the increasing availability of time-shared computer systems.

Innovations in computer technology have made it possible to automate many routine operator tasks. Decision-making functions, however, are often so complex and ill-defined that they defy automation. Consequently, man is still essential to perform such tasks as setting goals, diagnosing problems, and selecting courses of action. There is nothing to suggest that this need for human involvement in higher-level decision tasks will change significantly in future systems.

Technological advances in computer and communication systems present both threats to the quality of man-machine decision performance and opportunities to improve it. Complex systems for gathering and processing information can be built, allowing vast quantities of data to be assembled and displayed. Man's capacity to receive and process this information can easily be exceeded. Furthermore, as the scope of activity of systems increases, the consequences of erroneous decisions often become more severe. The problem is frequently compounded by reduction in the time available for effective decisions.

A number of investigations have already explored approaches to computer-aided decision making. These are briefly reviewed in Section II. However, our present knowledge of how best to facilitate decision-making processes is very limited, considering the many different kinds of decision tasks which people must perform.

Decision making as a task that system operators are required to perform, is typically ill-defined. It is often difficult or impossible to specify in advance just what decisions may be required or what data may be used in making them. It seems probable that this lack of definition is a major reason that system designers have rarely attempted to provide an explicit structure for decision-making functions.

A second barrier to effective design of system decision functions is the lack of adequate formal models or guidelines. Although there has been extensive research on theoretically optimum models for decision making, they are generally limited in scope or based on unrealistic assumptions. Consequently, these models have had little

application to operational problems. There is, therefore, a need to develop decision process models that are "reasonable" rather than "rational" and that are applicable to the design of man-machine systems.

Even though human decision making has been the subject of a great deal of research it is not well understood, due to the complex cognitive processes that are involved. This is a third reason for the lack of design guidelines. Relevant work has been done under a variety of topics, including statistical decision theory, game theory, concept formation, problem solving, risk taking, probability learning and signal detection. There is a need to organize and integrate the results of these various research areas so that they can be readily interpreted and applied to solving system design problems.

Another difficulty in considering decision making is that there is a lack of agreement on what the term means. In the present paper, a decision is defined as the selection of an alternative response to an inferred environmental situation about which complete certainty is lacking. This definition includes diagnostic decisions as well as action-selection decisions and is somewhat similar to a definition given by Roby (1964).

In summary, there is a requirement to develop concepts and techniques for unburdening decision makers in man-machine systems. Design guidelines for allocating decision functions, for simplifying and assisting operator decision processes, and for facilitating man-computer cooperation are needed.

This requirement has led to the development of the conceptual decision-process model outlined in Section II below. The model has the following long-term purposes:

1) To furnish a process structure for aiding the design of decision tasks.

2) To provide a framework for organizing and integrating knowledge derived from various areas of behavioral and theoretical research.

3) To identify areas needing further research by exposing gaps in our knowledge.

4) To assist in allocation of decision tasks in man-machine or multi-man systems.

5) To provide a basis for determining needs for aids to operator decision making.

RESEARCH ON COMPUTER-AIDED DECISION MAKING

The purpose of this section is to briefly assess the present state-of-the-art in computer-aided decision making.

In a recent article, Hunt (1968) reviewed various efforts to develop computer simulations of human cognitive processes, including decision making, and to produce "artificial intelligence" programs that can augment human thought processes. None of the projects that he describes are specifically intended to represent decision making behavior. Artificial intelligence programs, which generally are not designed as models of human thought processes, have been written to perform both deductive and inductive problem solving, including concept formation and pattern recognition. Newell and Simon's (1961) "General Problem Solver" programs are one of the few efforts to develop at least a first-level simulation of complex cognitive processes.

By far the most extensive research directly concerned with computer-aided decision making has centered on the use of Bayes' theorem as a basis for probabilistic information processing (PIP) systems. These systems are designed to employ human judgments of conditional probability relationships between possible situations and observed cues in automated diagnosis. The concept for such a system was described in an article by Ledley and Lusted (1960) on the use of computers in medical data processing. A paper by Dodson (1961) provided a modification of Bayes' theorem that greatly expanded its potential utility. Dodson also described how the modified theorem could be used as a key element in the development of automated threat evaluation and action selection systems. The following year Edwards (1962) published a description of a PIP system concept along with arguments which suggested the potential value of such systems. This paper was the first of a series of publications by Edwards and his associates describing extensive research into various aspects of PIP system and related aspects of decision behavior (Cf. Edwards, 1966; Edwards, Phillips, Hays and Goodman, 1968). A large-scale experiment comparing a PIP system with three different non-automated information-processing systems was carried out. The PIP system was found to be far more efficient than the other

systems in using unreliable data to produce diagnoses (Edwards) et al, 1968).

The Bayesian system concepts set forth by Dodson and by Edwards helped to stimulate a major program of research by Schum and others (Briggs and Schum, 1965; Schum, 1967) at Ohio State University. A large computer-based simulation of a hypothetical tactical reconnaissance system was used to explore the usefulness of PIP concepts for automated hypothesis selection and to investigate human performance in evaluating and using unreliable information. The results of this program of research have been evaluated in two recent papers (Howell, 1967; Howell and Gettys, 1968) which together present twenty-two principles for the design of decision systems. The most important result of this research is the finding that, over a broad range of conditions, automation can improve decision accuracy by 10-15%. The superiority over unaided human diagnostic decisions increases with increasing time or load stress and with decreasing input data quality.

A third laboratory evaluation of the automated Bayesian system concept has been carried out in a series of three experiments by Kaplan and Newman (1966). The basic task was to determine which of several bombing strategies was being employed by a simulated enemy whose bombs fell with some error distribution around the aiming points. Overall, the results indicated that, in comparison with unaided decision makers, the PIP system was again superior.

One of the first attempts to evaluate the PIP system concept in an operational setting has recently been reported by Gustafson (1969). Two versions of PIP were compared with four other methods of predicting patient length-of-stay in a hospital. The results indicated that, although it required the greatest amount of physician time per estimate, PIP yielded the best decision performance.

Gorry and Barnett (in press) have been conducting research to develop and evaluate the use of Bayes' theorem as an automated aid for sequential diagnosis. A computer program has been written that can guide a physician in selecting successive tests to arrive at a diagnosis. The program considers the informational value and cost of alternative tests in generating recommendations. Initial evaluation of the program was conducted using data from two hundred fifty case histories of congenital heart disease with previously established definitive diagnoses. The results showed that the program was capable of achieving accurate diagnosis with a relatively small number of tests.

A different type of man-computer decision system has recently been defined and explored experimentally by Miller, Kaplan and Edwards (1967, 1969). Their system concept is called JUDGE, an acronym for Judged Utility Decision Generator. The JUDGE system uses expert opinions to generate computer recommendations for action selection to maximize the total expected value over a series of such decisions. The problem for which JUDGE is designed is the commitment of tactical aircraft against targets which vary in value and occurrence in time. Human judgments provide, as inputs to the computer, statements about target values as new targets are identified. Using a set of complex decision rules and knowledge about mission success probabilities and aircraft availabilities, the computer then produces dispatching decisions. In experimental tests, JUDGE was found to be clearly superior to more conventional, unaided decision methods and performed close to a mathematically optimum level.

A number of other projects concerned with man-computer interactions for real-time decision making are noteworthy. Friedman (1962) proposed an automated system for evaluating alternative tactical command actions prior to taking action. His concept requires that the elements of the decision alternatives be fairly well defined. Ward and Davis (1963) described a concept for using a sample of human judgments along with the basic decision information to generate a multiple regression model that is a quantitative statement of the decision policy. This policy can then be programmed on a computer to produce decisions in future, similar cases. Work on a different approach has been described in a series of papers by Yntema and Torgerson (1961), Pollack (1964), and Yntema and Klem (1965). The basic concept is to program a computer to make decisions in multi-variable problems using subjective weights provided by human operators. A study by Vaughan, Virnelson and Franklin (1964) has also explored the use of expert judgment in defining and weighing factors relevant to action selections. They developed a unique display concept for a submarine command decision that graphically presents not only the recommended action but also the basis for its derivation. Shuford (1965) has described a major project that has produced a computer program (CORTEX) of decision theory processes for on-line use. The program actively assists the decision maker in formulating and assessing the problem and arriving at an optimum decision strategy.

Some problems are sufficiently well defined that formal algorithms could be programmed on a computer to systematically examine all potential solutions until an acceptable one is found. The time required to do this may be prohibitive, however. It may, in these cases, be possible to achieve more rapid solutions by combining human and computer capabilities in a heuristic process. Gagliardi, Hussey, Kaplan and Matteis (1965) have developed such a process for handling

certain complex, resource-allocation problems. The computer filters out most of the inappropriate solutions, leaving the human to make the final selections. Urban (1967) describes a concept for a man-machine search process to determine optimum combinations of variables. The operator bounds the search task and the computer determines the best criterion value. Successive iterations permit incremental approaches to the optimum combination of values.

Two recent papers have considered the utilization of computer-aids by decision makers. Shaffer (1965) explored the use of a computer-generated solution in a queue-serving problem. Subjects could accept or modify the recommended solutions. The results showed that subjects tended to degrade optimum solutions but improved inferior ones. Hanes and Gebhard (1966), in a major program of research, found that tactical commanders will accept computer-generated decision recommendations with consequent improvements in performance provided that certain conditions are met.

A CONCEPTUAL MODEL FOR DECISION TASKS

Scope and Limitations

The decision process model is conceptual rather than mathematical and is intended to apply to man-machine performance in real decision situations. The model, therefore, does not make unrealistic assumptions about levels of knowledge or information-processing capacity. Such assumptions often are present in the "rational man" models found in many theoretical studies of decision processes. The model is not descriptive of observed behavior, but rather represents an idealized process. In this sense it represents a "reasoning man" concept.

The model, although based on many sources, is preliminary and tentative. It is intended to apply to a broad variety of decision situations, but not necessarily to represent any single one. In any given decision situation, the indicated order of the process steps might need to be modified. Some of the steps might be omitted, at least so far as being explicitly performed. The model indicates temporal relationships only to a limited degree and specific methods for accomplishing the prescribed steps are not defined. Only a few of many possible process loops are indicated. Finally, the entire process, as shown, is only a single iteration of many that might be required, either sequentially, in parallel, or hierarchically, to carry out a decision task.

Model Summary Description

The decision process model is divided into three stages: problem recognition, problem diagnosis, and action selection. These are described briefly below. For a more detailed description and for references which provided inputs and a background for the model, see Schrenk (1969).

Problem Recognition. The steps which make up problem recognition are shown in Figure 1. Information inputs and system objectives provide the basis for recognizing the need for a decision. The urgency and the importance of the problem in relation to other problems need to be assessed and the time and effort which should be devoted to the decision task evaluated.

Problem Diagnosis. This phase is illustrated in Figure 2. Defining the possible situations which may be causing the problem is a process of hypothesis generation. The next step is to evaluate the initial or a priori likelihood of each hypothesis. At this point, the need for more information should be considered. This should include consideration of the costs and payoffs for correct and incorrect diagnoses. If more information is desired, then the possible data sources are defined. Next, the diagnostic value and costs for each source are evaluated in order to select the most useful. Action is then taken to acquire information. As it is acquired, the likelihoods of the alternative situation hypotheses are reassessed and the need for additional information again considered. Before making a final diagnostic decision, the favored hypothesis should be reviewed to see if it is consistent with all of the available information.

Action Selection. The processes of action selection are shown in Figure 3. An initial series of steps provides the basis for evaluating possible actions. Initially the goals to be achieved are defined. The relevant value and time factors for judging the desirability of action outcomes should be specified and their relative values established. Finally, a risk philosophy or strategy for successive decisions is needed.

The development and evaluation of alternative courses of action is next. Within the constraints of whatever operating doctrine may be provided, the action alternatives are generated and their possible outcomes are forecast. A gain or loss value needs to be estimated for each possible outcome. The relative probability of occurrence for each outcome also needs to be judged. These factors are then used to specify the expected value of the possible outcomes for each alternative action and consideration is given to the cost of taking the action. The suitability of each action also is judged on the basis of the strategy or risk philosophy previously defined. Since many uncertainties are usually present in the action selection, it may be desirable to postpone an action decision in order to obtain more information. The information selection process is similar to that described for diagnosis. Once a best action has apparently been identified, a final check should be made to determine that it satisfies the value and time criteria and that any possible adverse consequences can be accepted or avoided. If not, then new action alternatives may be required. At the end of the process a course of action is chosen. This typically involves an irrevocable commitment of resources. Action implementation may include determining the method for carrying out the decision and for monitoring its effects.

FUTURE DEVELOPMENT

A number of steps are envisioned for further development and validation of the conceptual model. The first step is to carry out a more thorough review of the literature to extract pertinent findings and principles. These will be classified and integrated within the framework of the individual process steps. Following this organization, the available knowledge will be evaluated to define, to the extent possible, specific human capabilities, limitations and tendencies relevant to accomplishing each step. This evaluation can then be used to generate recommendations for allocation of task steps between man and machine. Requirements for aids to facilitate performance of process steps assigned to human components will also be derived.

Validation of the usefulness of the model can perhaps best be carried out by applying it to specific decision system problems. Such use of the model can be expected to reveal requirements for revision and for greater detail in various portions of the model. If several such applications can be carried out in sequence, it should become possible to provide fairly useful engineering design guidelines for improving decision-making performance in man-machine systems.

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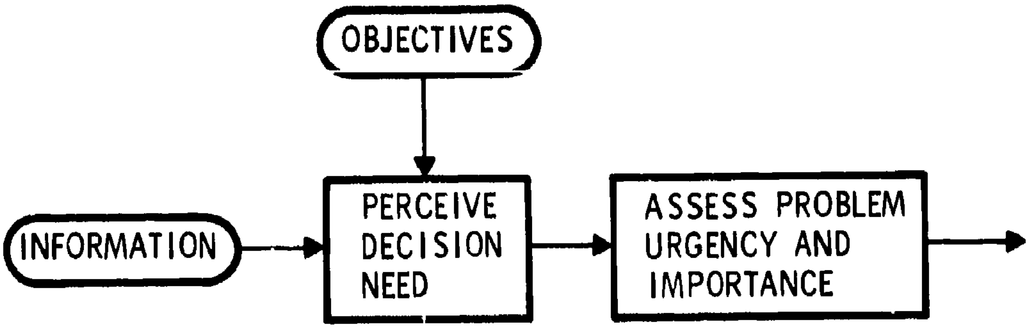

FIGURE 1. A Conceptual Model of a Process for Problem Recognition.

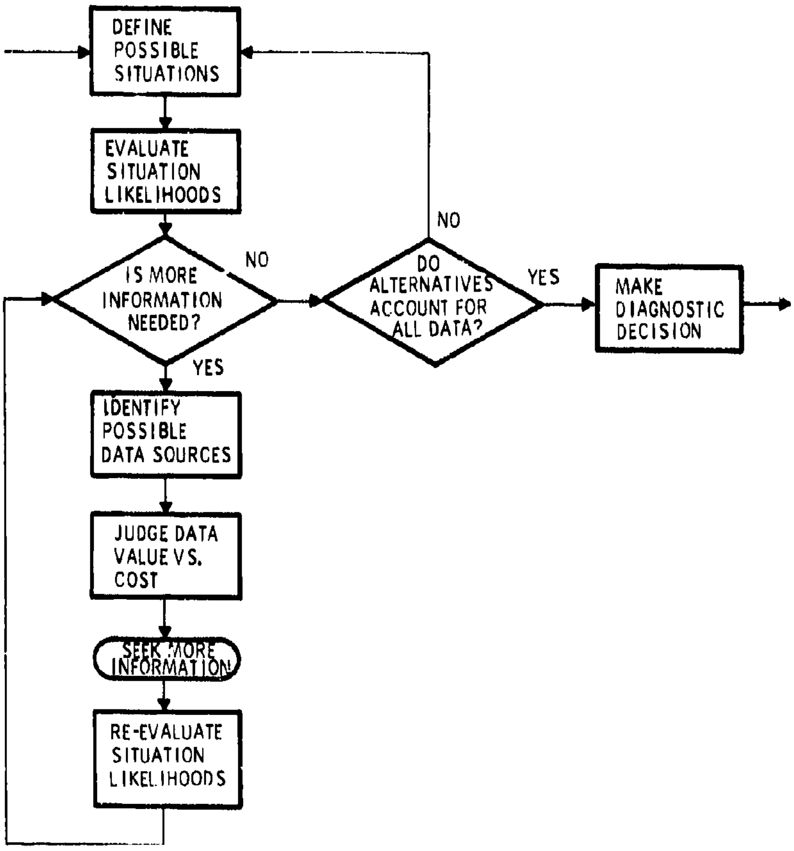

FIGURE 2. A Conceptual Model of a Process for Problem Diagnosis.

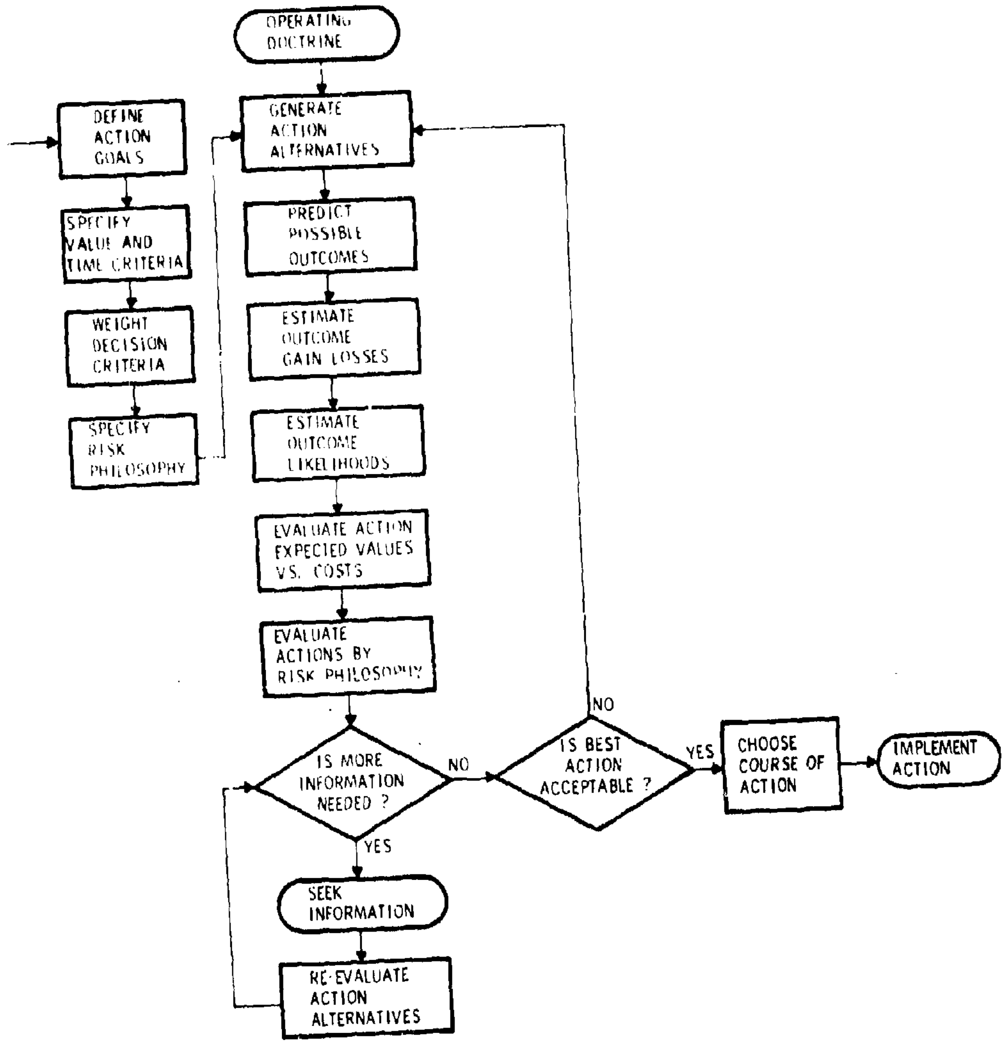

FIGURE 3. A Conceptual Model of a Process for Action Selection.

Recent Progress in the Monte Carlo Simulation of Man-Machine Systems

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Abstract

Three Monte Carlo simulation models are described. The models have been developed over the years by Applied Psychological Services, and deal with the simulation of missions and tasks performed by crews in the ranges of 1-2, 3-20, and 20-100 men. All deal principally with variables of interest to the psychologist and the human factors specialist and include effects such as stress, proficiency and morale as well as the more usual variables required to describe the equipments, the work stations, and the time frames selected.

The development of the first model is stressed and particularly how improvements have been made to extend its ability to cope with greater numbers of real world situations such as: application of the kernel of the model to subject-to-computer interactive situations. It is this most recent development, initiated under the guidance of the AMRL of the Air Force's WPAFB, on which the paper concentrates. Here the field of digital simulation has taken a new step--to interface one or ore live subjects with the digital simulation model. Generality of digital simulation to many man-machine systems is thereby combined with the reality and appeal of direct subject participation. The approaches taken to this work are presented.

Introduction

Now in its second decade, the "science" of experimentation using Monte Carlo simulation continues to enjoy expanding interest and support. This has been made possible principally by the advent of the symbol-manipulation equipment which we call the digital computer. The major features of many real life phenomenon have come under its scrutiny; among these are population projections, traffic flows, economic fluctuations and corporation planning doctrine. The field of human factors research, which has the interest of all at this meeting, has not been immune to this trend. Why is increased attention being devoted to this one of the many forms of simulations? First, the cost of computation has been markedly reduced in recent years and computing systems have been much more readily available. In addition, many of the equipment systems being designed today, particularly in the military and space fields, have become costly. This makes simulation before equipment production more attractive. Also, the newer systems are often more complex than before; this renders the capability of the man in the man-machine system all the more questionable, and again makes simulation desirable in an attempt to avoid a man-machine mismatch.

A Sketch of Three Models

Our purpose today is to present some recent progress in the use of Monte Carlo simulation. To do this we shall first present a brief sketch of three simulation models developed and utilized over the years by Applied Psychological Services. Following this, a recent effort to utilize one of these models in an unusual interactive way will be discussed.

All three models have been prepared to simulate men operating and maintaining equipment. In each case a task analysis or mission event sequence forms the basic computer input. All have major simulation variables to reflect the realities of the equipment, the mission itself, and one or more important time functions. Yet they all possess in addition (and this represents their distinctive feature for us) psychological and social variables pertaining to the operator or to groups of operators. Examples of these are stress, orientation, proficiency, mental load, and fatigue. In addition to the more common results such as equipment reliability, working hours, and operator failures which one might expect from Monte Carlo models, these three models generate data on personnel performance, morale, cohesiveness, goal orientation, and man-machine system efficiency. All yield output tabulations reflective of the man-machine system under study in order to predict system "performance," personnel overloads, periods of ususual stress and excessive delays. All are based on

the Monte Carlo approach in which pseudo-random numbers are repeatedly used to select a number from some desired statistical distribution for use during the simulation, or to form the basis for making a decision.

The principal differences between the three models are: (1) the number of operators simulated simultaneously, and (2) the level of detail simulated. These differences and other major features are shown in Figure 1. We are not discussing here merely a single model with extensions made from time to time in order to expand its capability to handle greater numbers of operators. Rather there are three distinct models-each with its unique approach and logic. The first model, for simulating one or two men, can accommodate up to 300 individual operator actions, by each operator of a few seconds or minutes duration each. We will have more to say about this model later.

In the largest model, a crew of from 20 to as many as 100 men may be simulated. The mission is composed of work units which may be minutes or hours in duration and the total mission may last for several dozen days. The limit here is principally a practical one based on computer running time. This model has simulated the performance of a naval submarine crew on a multiday mission. The following list of features and variables will generally give the flavor and complexion of this model:

- cross training of men in alternate specialties
- sickness of crew members
- pay grades and promotion
- communications between work stations
- equipment failures
- postponement of work of lesser importance
- proficiency of each crew member and its improvement
- time worked by crew members including regular hours
- overtime hours in primary as well as secondary specialties
- the man-machine system efficiency

This lower limit of 20 man crews which can be simulated by this large model is somewhat artitary. It is intended only to imply that the relationships and logic utilized tend to lose meaningfulness for smaller and smaller work groups. Thus, the intermediate scale model, the last to be developed was designed to full the gap, between very large crews of several dozen men and the two man case. Like the larger model, it can also simulate a multiday mission. A corresponding partial list of features and variables for the intermediate model is:

- consumables
- sleep

Figure 1. Major Features of Three Man-Machine Simulation Models

Number of Men	Duration of Missions	Duration of Work Task or Event	Number of Work Tasks or Events	Model Status
1-2	Minutes or hours	Seconds or minutes	Up to 300	Completed. Tested, used and modified often. Documented.
3-20	A few days	Tenths of hours	80 per day	Programed Being tested Preliminary report published
20-100	Many days	Tenths of hours	100 per day	Completed. Tested in one real situation

physical capability of the man
emergencies
equipment failures and repair
mental load
work hazard level
physical incapacitation
fatigue and,
work pace

Consider now the use of the first of these models. A sequence of jobs for each operator called subtasks is prepared. These are simulated by the logic of the model one-by-one so as to allow operators to: work independently or together, wait for each other, talk to each other, monitor and operate controls and displays, wait for equipment, skip nonessential subtasks if the operators are too busy, make decisions which can alter the subtask sequence, and recycle if required in the event of an operator failure.

Flexibility in simulation is provided in the model though the ability to allow parametric variation of such factors as the speed of the operators, their stress breaking points, and their mission time limits.

This model has been under development and in use for over a decade. It has been tested against real life and against laboratory controlled criteria, and has found to give reasonable, interesting, and valuable results. It has undergone reprograming and expansion often and has been used for airborne, shipborne, and spaceborne missions by the military service and several commerical firms.

The major results from using this model are:

- the probability of success--that is the percentage of times that the prescribed sequence of subtasks was completed within the time limit.
- the shape of the stress function during the simulation.
- the distribution of time as spent in working, waiting, and in repeating work not properly performed.

Recent Model Developments

With the guidance of Air Force personnel at the Wright-Patterson Air Force Base's Human Engineering Division, this model has just

recently been adapted for subject-to-computer interaction. The program for the two man model has been segmented and imbedded in a control program we shall call SIM prepared by WPAFB personnel. This allows dynamic on-line interaction between one or two subjects and the computer simulation.

Here we have an experiment called an exercise in which one or two subjects are seated at independent CRT displays. These are IBM 2250 terminals capable of display of graphic as well as alpha numeric or symbolic information. During the exercise, which may run say 15 to 25 minutes, the subject is sequentially presented with a series of display presentations generated under control of the SIM program. Thus we have a stimulus presentation scheme in which the subjects can operate any two operator device as simulated by the two subject display terminals. Their work in general consists of inspecting a presentation and deciding what they would do if they were operating the real system. Once they decide this, the two man model simulated a segment of that work. This is continued repeatedly.

The overall process of the exercise is shown in Figure 2. The exercise begins with the reading of parameters defining the display and the generation of the initial situation.

Then there follows a series of operations in which the subject and the experimenter indicate to the computer their readiness to proceed, the first display situation is generated and presented, and a clock is started to keep time of performance. The subject then has the opportunity to study his display. When he is ready to make a choice of alternate courses of action he selects one of the appropriate controls on this terminal. There are as presently programed, a maximum of 15 different push buttons on his terminal to which he has access. Selection of one of these 15 push buttons indicates the subject response to the situation which he sees. Each press of a push button also represents a unique task to the two man simulation subroutine. That is there are 15 prestored sequences of subtask data, corresponding to the 15 push buttons.

Normally, the two man model accommodates up to 300 subtasks for each operator on a mission. Each set of N iterations of the mission is called a run. (a 100 iteration run of 300 subtasks for each operator takes about 5 minutes on the IBM 7094). In this interactive experiment the program has been modified to simulate many runs in one exercise. But now each run, as initated by a subject push button action, will represent a maximum of only 25 subtasks.

Each control action by the subject is detected by SIM which causes the

subtask data--up to 25 subtask--to be brought from the computer's disc file into common core storage for simulation. The time limit normally allocated to this operation is also similarly stored and called.

Thus, for each push button pressed by the human subject, selected as a result of the display, N iterative simulations of the selected family are performed under control of the two man model. During the course of each subtask simulation the following basic elements are determined:

- the stress of the simulated operator
- the simulated execution time based on the operator speed factor, stress level, stress threshold and average performance time
- the success or failure of the subtask

Three basic results calculated the model are made available to SIM. These are:

- number of iterations out of N which were successful
- average amount of time used
- average stress at the end of the run simulation for each family

Following the processing of the selected "family" of subtasks by the two man model, control is returned to SIM which determines the balance of the time available to the subject, notifies the subject as to status of the exercise, and recycles to present, at the appropriate time, the next display situation. The timing and content of the presentation of the next display is based on the subject's performance both in terms of selection of a reasonable push button and of proper timing for it. The SIM program also provides a display to the experimenter of the current performance results by subject.

This entire process of display, reaction by the subject, simulation by the two man model, and evaluation by SIM is repeated over and over. During the course of this exercise a maximum of 150 subject-initiated calls may be made for task families to be simulated. Of course there is no restriction on their sequence.

At the end of the exercise, a summary is made of results of the two man model simulation. These simulated results include data on successes, time worked, stress, nonessential subtasks ignored, and time spent in repetition of failed subtasks.

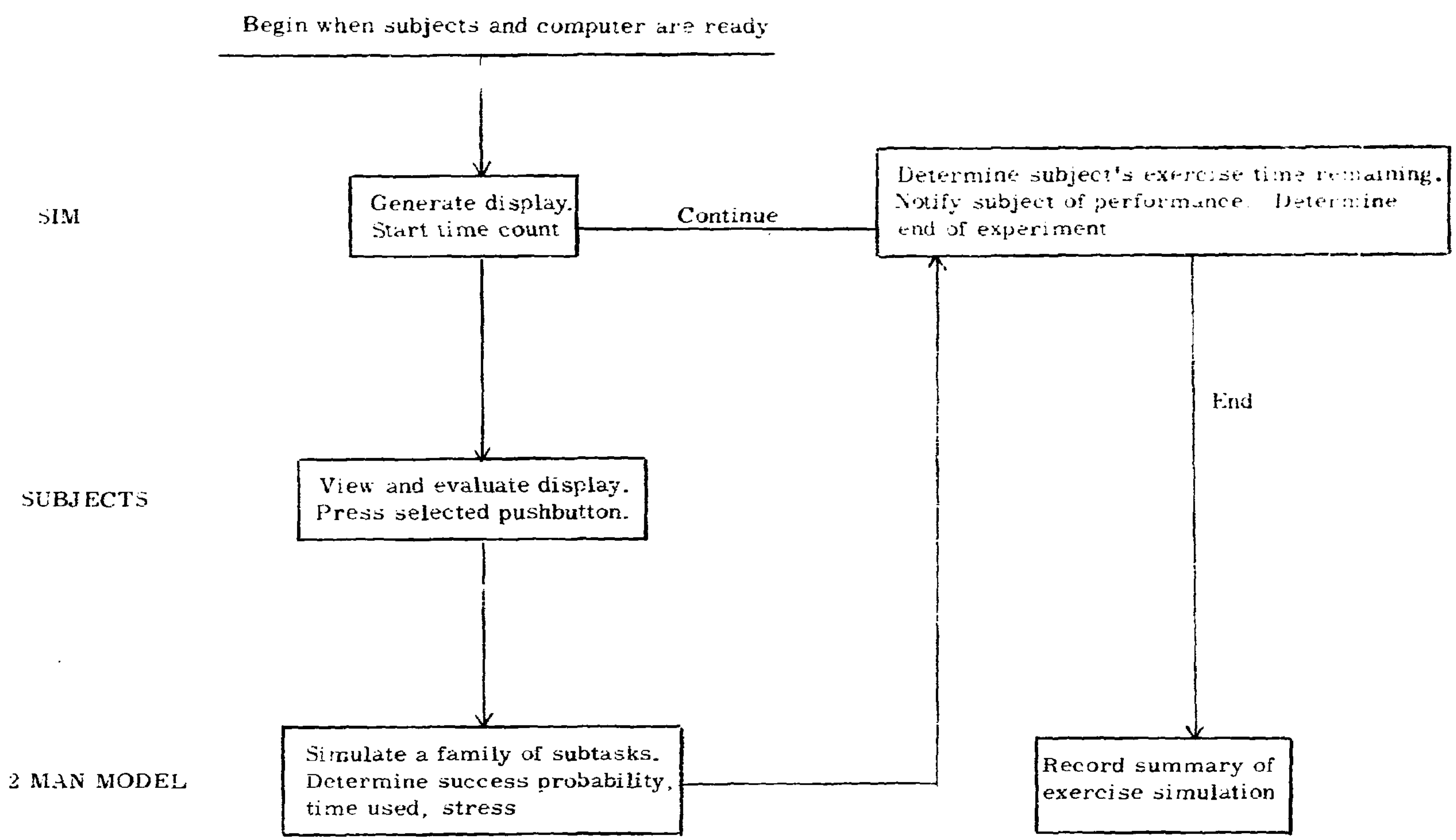

Figure 2. General outline of interactive exercise.

Summary

In this scheme critical decision making, a function usually left for the human in man-machine systems, remains with the subject. At the same time we are still able to simulate on the computer the operation of some expensive or unavailable console or other equipment. Each action by the subject calls forth the computer to fill in with the dog work of simulated machine operation, and the computer enhances the subjects performance by simulating their performance and that of their equipment.

Thus, the generality of digital simulation of man-machine system is combined with the reality and appeal of direct subject participation. Preparation for this experimentation has require interdisciplinary cooperation in the fields of psychology: Monte Carlo simulation technology, military doctrine, and remote interactive computer terminals. It is too early now to predict the degree of success of the approach described. It is one of several being applied to the problem of entering production with a high confidence in a complex man-machine system. It represents a new step--an interface of subjects at a "standard" console with computer simulation. It appears to us to be a melding of promising approaches.

Acknowledgements

The basic work on the models here described was performed under contract between Applied Psychological Services and the Office of Naval Research. The interactive simulation development was performed under contract with the Wright-Patterson Air Force Base. We acknowledge the contributions of the many, at both of these organizations, who contributed materially to our thinking.

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MATHEMATICAL MODELING AND GRAPHICAL DISPLAY OF HUMAN MOVEMENT*

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ABSTRACT

A joint Boeing-JANAIR research effort is developing a standardized cockpit geometry evaluation tool. The program is designed to provide an evaluation tool from the conceptual phases of a cockpit development for determining the physical compatibility of any sized crewmember operating within the crewstation. A 23-joint, three-dimensional mathematical man-model capable of synthesizing joint locations during task performance is the key element of the development. Constrained optimization of a non-linear objective function is used to effect task performance. A computer program system has been developed to store and retrieve data, perform geometry evaluations, and output the results in various forms including computer graphics. Graphical displays of the man-model performing in a crewstation have been used extensively during the development.

INTRODUCTION

An understanding of human movement parameters has been a perplexing problem to man for some time. Beginning with the earliest known artistic records, man has attempted to capture and understand various aspects of the physical activity of man. Ancient Egyptians painted tales of man with spear in hand preparing to obtain food for his family. Today we find the scientist trying to predict the effects of an astronaut's movements on a spacecraft in a gravity-free environment. Similar to the latter is the functionability of man in modern-day aircraft.

The cockpits of modern-day aircraft are intricate and highly complex. Consequently, the man-machine interface in these aircraft is an extremely important consideration in the design. Scientists are concerned with all aspects of man in the cockpit. One of the areas of consideration is the physical compatibility of the man and the machine. As cockpits became more complex, it is apparent that an evaluation tool is needed to assess the physical compatibility of any sized crewmember performing in any crewstation. This tool, to be most useful, should be available in the conceptual phases of a crewstation design.

*Part of the research reported in this paper was conducted for the Joint Army Navy Aircraft Instrumentation Research (JANAIR) Program under Office of Naval Research Contract N00014-68-C-0289, NR 213-065.

A research program was initiated towards this end. This research effort, the Cockpit Geometry Evaluation Program, is being conducted as a joint Boeing/JANAIR effort. The Joint Army Navy Aircraft Instrumentation Research (JANAIR) Program is a U. S. military research and development project directed toward providing the technical knowledge for improved mission effectiveness of future military manned aircraft systems. The results of this particular research program, however, will not be limited to aircraft cockpit geometry only. Any crewstation geometry where human beings are an integral part can be evaluated if appropriate criteria are established.

The Cockpit Geometry Evaluation (CGE) Program is developing a basic Computer Program System to examine this functional compatibility between any sized seated operator and any crewstation. Cockpit geometry is defined as the physical layout, that is, locations, shapes, and arrangements of the entire crewstation complex - displays, controls, seats, personal equipment, windshield/canopy/windows, interior surface shape, and openings for ingress and egress.

The heart of the evaluation method is a computerized mathematical man-model capable of synthesizing three-space joint locations for any sized operator performing prescribed tasks. Other research efforts have synthesized two-dimensional joint movement; however, this effort is the first known attempt to model completely the complex three-space human movement parameters.

The Cockpit Geometry Evaluation Program was planned as a six-phase effort, each of 12 months' duration, as shown in Figure 1. The program is a joint experimental laboratory, computer modeling, and validation effort. The key to the program is the modeling of human movement. Each year of effort will provide an end product of immediate use to military and civilian designers. Currently the program is in Phase II of the effort.

In Phase I of the program, the following major efforts were completed:

- A 23-joint link man-model (BOEMAN-I) was defined from existing human data.
- Mathematical optimization techniques were developed to synthesize joint locations during task performance.
- New human data requirements were defined.
- Basic crewstation geometry descriptor routines were developed.

- Visual interference assessment was developed.

- Reach assessment was developed.

- The Cockpit Geometry Evaluation Computer Program System integrated all of the computer programs into one system.

The final reports of Phase I listed in References 1 through 5 provide detailed information on these areas.

In the current Phase II of the program, the following items are undergoing development:

- Body segments placed around the link system of BOEMAN-I to create a three-dimensional man-model (BOEMAN-II).

- Definition of three-dimensional cockpit components with the capacity to simulate relocation of the controls within the crewstation.

- Physical and visual interference assessment.

- Additional human data is being gathered.

- Improvements to and evaluation of alternate man-models.

- Updating the Computer Program System.

- Acquisition of additional human movement data to improve and validate the man-model.

- Examination of future phases of the program.

THE COCKPIT PROBLEM

The validity of present cockpit evaluations depends on five factors: 1) integrity, skill, and experience of the evaluator; 2) adequacy of the criteria; 3) limitations inherent in the evaluation methods used; 4) control of the test conditions; and 5) availability of test equipment. Currently, drawing reviews, mockups, mathematical models, flight simulators, and prototype flight-test techniques are used to evaluate cockpit geometry. These methods have been refined over the years and do produce useful data, yet they cannot take into account the full variability in flight crew anthropometry. Figure 2 illustrates this problem and the associated penalties of flow time and cost for, in this case, the military.

In general, all the methods presently used to examine and evaluate crew performance, both mental and physical, have some limitations. Those that can be applied early in a design program, for example, activity flow diagrams, limited mathematical models, and mockups, are limited in prediction accuracy. In addition, they are subject to the bias of the analyst and lack standardization of input data, method, format, and output descriptors. The more precise methods, such as full dynamic flight simulation and prototype flight test, occur so late in the product development program that any needed redesign indicated by them is usually costly, since designs are frozen by this time and manufacturing commitments made. Therefore, if an effective standardized evaluation tool were available from the conceptual phases of the development, improved designs and significant cost savings would result.

MAN-MODELING TECHNIQUES

The proposed solution to the evaluation problem centers around the mathematical modeling of the crewmembers and the crewstation. Specifically, the approach designated that the size of the man-model must be adjustable so that it could represent any sized crewmember. In addition, the synthesized movement parameters of the man must be similar to those of the human population.

Dempster (6) laid the groundwork for modeling man with an adjustable link system. The link concept was applied to a system of bones in the human body. The links run from joint center to joint center of the bones most prominently associated with human movement. With some minor modifications to Dempster's excellent work, BOEMAN-I, shown in Figure 3, a 23-joint, adjustable link-man was created in Phase I of the program. In Phase II, three-dimensional shapes are being placed around the link system so that physical and visual interference problems can be identified. The result is BOEMAN-II shown in Figure 4.

In Phase I, human data describing the 1st through 99th percentile military pilot was collated and published in Reference 5. Included in this document are anthropometric, ergometric, joint angular limit, body parameter, and visual characteristic data. These data were used to define the 23-joint baseline man-model, BOEMAN-I, and the three-dimensional man-model, BOEMAN-II. In addition, this collation of such a wide variety of human data should prove useful to individuals concerned with any man-machine interface. This document will continue to be updated and expanded with pertinent information through the duration of the program.

While the human data document has collated much of the data needed to develop a fully articulated man-model, there are requirements for additional human characteristics and capabilities. These new data requirements were generally described in Reference 7 and some of the key data required, time required for development, and the critical date the data are needed are shown in Figure 5.

The development of a computerized mathematical man-model has been and will continue to be the key to the creation of a computerized geometry evaluation tool. The man-model which received the greatest effort to date is a mathematically constrained optimization model, which synthesizes joint locations and body segment orientations during task performance.

In Phase I, the development of the man-model was conducted in stages to simplify the complexity of the study. These development stages of Phase I are illustrated in Figure 6. Stage 1 provided for unconstrained movement of only one arm with a rigid spine link. Stage 2 placed angular constraints on the movable joints of the model, and Stage 3 added constrained movement of the spine. In Stage 4, links for the other arm, head and neck were added and all angular constraints were removed. This provided unconstrained movement of the entire man above the base of the spine. Stage 5 placed angular constraints on all the joints. In Phase II, lower torso movement is being developed along with the addition of three-dimensional body segments.

The skeletal framework of the baseline man-model is made of five sequential link-systems, all beginning at the bottom of the spine. The links with lengths L_i and connecting joints P_i are adjustable to fit the different sized pilots to be simulated.

The problem of modeling the physical motion of a human can be stated as follows: Produce a body configuration for the man-model which approximates that of a human at any specified instant during the execution of any task. The task for the man-model is mathematically defined by specifying the way in which certain body segments, such as the hand, are to move. The other body segment trajectories during the task are then calculated by the man-model.

The reference coordinate system is located at the bottom of the spine. The location of any point on a body segment can be found once the Euler angles Z_j $(1 \le j \le n)$ that express the relative orientations of adjacent links and the link-lengths L_i are known.

Each sequential system of body segments, beginning with the bottom of the spine, is associated with an increasing sequence $\{I_i\}$ $(i = 0, 1, \ldots, m)$ of positive integers, where m is the number of body segments in the system. For a given system, each joint P_{I_i} lies at the distal end of link I_i and is used as the coordinate center for link I_i. In displaying a body configuration, each joint P_{I_i} is first expressed in this "local" coordinate system. The Euler angles Z_{I_i} and link lengths L_{I_i} are used to define a series of translations and rotations which transform the point P_{I_i} from the I_i-system into the base-of-the-spine coordinates.

The use of the Euler angles of the model as rotation angles is illustrated in Figure 7. In general, three-space rotation from system I_i to system I_{i-1} can be expressed by finding the corresponding Euler angles θ_{I_i}, φ_{I_i} and ψ_{I_i} as shown. Those Euler angles which are variable at each joint are a function of the degrees of freedom of that joint. For example, the shoulder joint has three degrees of freedom while the wrist joint cannot twist (ψ) and hence has only two. Thus, one or more of θ_{I_i}, φ_{I_i}, and ψ_{I_i} may be a parameter Z_j in the vector $\underset{\sim}{Z}$ of variable angles. These three angles are used to calculate a rotation matrix T_{I_i} which transforms the coordinates of a point in the I_i system to the I_{i-1} system. Hence the cockpit reference coordinate vector $P_{I_i,0}$ of $\underset{\sim}{P}_{I_i}$ is a vector function of Z_j. Using common parlance, we write this as a function of the entire vector $\underset{\sim}{Z}$; e.g., $\underset{\sim}{P}_{I_i,0} = \underset{\sim}{P}_{I_i,0}(\underset{\sim}{Z})$.

An explicit formula for $\underset{\sim}{P}_{I_i,0}(\underset{\sim}{Z})$ can be obtained by using the matrices $T_{I_i}(\underset{\sim}{Z})$ ($i = 1, \ldots, n$) and translating and rotating to the bottom of the spine. This gives

$$P_{I_i,0} = M^i \underset{\sim}{t}_{I_i} + M^{i-1} \underset{\sim}{t}_{I_{i-1}} + \cdots + M^2 \underset{\sim}{t}_{I_2} + M^1 \underset{\sim}{t}_{I_1} \tag{1}$$

where M^i is the matrix product

$$M^i = \prod_{k=1}^{j} T_{I_k} \text{ and } \underset{\sim}{t}_{I_i} \text{ is the link-vector } \begin{bmatrix} 0 \\ 0 \\ L_{I_i} \end{bmatrix} \tag{2}$$

For each task the man-model is required to move a point P_{I_m} on the specified hand from control point $\underset{\sim}{A}$ to control point $\underset{\sim}{B}$. The task motion for the point P_{I_m} is specified to move along the directed line segment $\overrightarrow{AB}$. The man-model performs the task stepwise by dividing the task-motion into steps of successive points $\underset{\sim}{C}_q$ ($q = 1, \ldots, M$) along $\overrightarrow{AB}$, where $\underset{\sim}{C}_1 = \underset{\sim}{A}$ and $\underset{\sim}{C}_M = \underset{\sim}{B}$, and by solving for a body-configuration vector Z^q corresponding to each intermediate "control point" $\underset{\sim}{C}^q$. Thus, the task definition for step q is expressed as a vector equation in functions of $\underset{\sim}{Z}$:

$$\underset{\sim}{P}_{I_m,0}(\underset{\sim}{Z}) - \underset{\sim}{C}_q = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{3}$$

To force this condition on the solution vector Z^q, the solution procedure used in this model requires the use of a penalty function $r_k |g(\underset{\sim}{Z})|^2$, where r_k is a positive real number and $g(\underset{\sim}{Z})$ is the constraint vector given by

$$\underset{\sim}{g}(\underset{\sim}{Z}) = \underset{\sim}{P}_{I_m,0}(\underset{\sim}{Z}) - \underset{\sim}{C}^q \tag{4}$$

The basic problem-solving technique for finding the orientation angle vector $\underset{\sim}{Z}^q$ at step q is non-linear optimization of an objective function. Non-linear constraints are imposed by vector equation (3), using the penalty function formulation shown above. The objective function to be minimized is a non-negative real-valued function of $\underset{\sim}{Z}$ called $f(\underset{\sim}{Z})$.

Hopefully, when $f(\underset{\sim}{Z})$ is minimized at each step C_q, the link orientations corresponding to the optimized Euler angle vector $\underset{\sim}{Z}^q$ would be similar to those of humans performing the same task. Minimization of $f(\underset{\sim}{Z})$ alone in the present model would put the body in a "preferred" position. A unique vector $\underset{\sim}{Z}^o$ of "preferred" angles is specified and $f(\underset{\sim}{Z})$ is given the form

$$f(\underset{\sim}{Z}) = \sum_{j=1}^{n} W_j(Z_j - Z_j^o)^2 \qquad (5)$$

where the W_j are weighting factors expressing the relative importance of minimizing the squared deviation $(Z_j - Z_j^o)^2$ of angle j $(1 \leq j \leq n)$ from its preferred value Z_j^o. The Davidon (8) variable metric method, as described by Fletcher and Powell (9), is used for minimization with a penalty function based on equation (4). The function to be minimized becomes:

$$F_k(\underset{\sim}{Z}) = f(\underset{\sim}{Z}) + r_k \, |\underset{\sim}{g}(\underset{\sim}{Z})|^2, \qquad (6)$$

where r_k increases with increasing k. That is, a sequence of minima $\underset{\sim}{Z}^k$ are found for the modified objective function F_k for $k = 1,2,3,$ . . .. Under favorable conditions, $F_k(\underset{\sim}{Z}^k) \to f(Z^q)$ where $\underset{\sim}{Z}^q$ is the solution, as $\underset{\sim}{g}(\underset{\sim}{Z}^k) \to \underset{\sim}{0} = \underset{\sim}{g}(\underset{\sim}{Z}^q)$.

The formulation expressed in equations 1-6 has neglected to provide for limitations on the motion of a human. That is, the freedom of motion of the body is limited by restrictions on the variable Euler orientation angles Z_j. This is expressed by the inequalities

$$a_j \leq Z_j \leq b_j \qquad (1 \leq j \leq n) \qquad (7)$$

where a_j and b_j are the lower and upper bounds, if any exist, for angle Z_j. The inequality constraints in equation (7) are removed by reformulation of the problem. An unconstrained parameter vector Y is used in place of Z. A vector function G is defined on n-dimensional space such that

$$\underset{\sim}{Z} = \underset{\sim}{G}(Y) \qquad (8)$$

and such that the components of Z satisfy equation (7). In the present model, G is defined by the set of equations

$$Z_j = G_j(\underset{\sim}{Y}) = a_j + (b_j - a_j)\sin^2 Y_j. \qquad (9)$$

Additional mathematical routines are presently being developed to place three-dimensional body segments around the link system. In conjunction with this effort, routines are also being developed to determine if physical and/or visual interferences have occurred during task performance. Visual interference occurs if the views of a task control location are blocked at any time during task performance. Physical interference occurs if any body segment contacts any element of the cockpit or any non-adjacent body segment during task performance. Methodology for visual interference avoidance is presently being developed and future phases of the program will develop methodology for physical interference avoidance.

VALIDATION

In Phase I validation criteria developed held that the man-model must closely simulate the joint movement paths of any sized human operator at any workstation. Limited human movement data were obtained using a multiple camera filming technique. A rigorous statistical analysis was derived which compared the synthesized arm joint locations of the man-model against the mean of each subject. Comparisons were made at joint locations of each task where the greatest discrepancies between the model and the subjects were expected to occur. In general, the results indicated that some statistical differences occur; however, practically, they appear negligible. Recent evaluations of the statistical analysis indicate it is too restrictive; hence, new techniques are being derived.

COMPUTER PROGRAM SYSTEM

During Phase I a computer program, called the Cockpit Geometry Evaluation Computer Program System, was generated. The program is written in FORTRAN IV and utilizes the large storage capacity and speed of the CDC 6600. The program system is a collection of smaller subprograms that provide the capability to (1) store large and varied amounts of data, (2) retrieve selected subsets of data, (3) calculate human body joint locations and numerical performance indicators, (4) display data and computations in tabular, graphical or pictorial form, and (5) perform the validation of the man-model.

These capabilities are largely modularized into five separate programs:

1) Storage

2) Retrieval

3) Geometry Evaluation

4) Output

5) Man-Model Validation

The storage program creates the overall data bank of information which contains such terms as anthropometric and physical characteristics of various human populations and the crewstation to be evaluated. The retrieval program selects those data specified by the user to be evaluated.

The geometry evaluation subprogram is in essence the man-model portion. The man-model with specified link lengths is required to perform a task sequence in a given cockpit configuration. For each task, paths of motion are formed by the successive calculation of the locations and orientations of the man-model's joints using the mathematical formulation discussed previously. The evaluation consists of certain quantitative measures, called numerical performance indicators, which provide comparisons between tasks, task sequences, link sizes (length and mass), or workstations. Program OUTIO provides a printed history of the evaluation run, data for graphs and charts, and a magnetic tape of data for man-model validation.

GRAPHICAL DISPLAYS

Computer graphic simulations and displays are receiving wide attention and development in cockpit design. Windshield displays, vision envelopes, cockpit geometry displays, and man-model movements have been developed. In the Cockpit Geometry Evaluation Program, computer graphic displays of the crewstation geometry and the man-model have been used to:

- o determine the accuracy of the cockpit geometry computer descriptor routines
- o evaluate and improve the mathematical modeling techniques of the man-model
- o discover physical and visual interference problems

Orthographic, isometric, and perspective displays of the man-model performing various tasks have been used extensively to improve the mathematical modeling techniques. The computer printout lists the synthesized joint angular data of the man-model at various positions in the task; however, this data is more meaningful when the man-model is graphically displayed at these positions. Subjective and quantitative judgments of how well the man-model is simulating human movement can easily be made.

In the future, computer graphic techniques such as animated film sequences may be superposed on human movement films for man-model validation. In addition, interactive graphical scope displays of the man-model in a conceptual crewstation may be used by the designer to perform evaluations even before the first draft of a proposed crewstation are released. This would allow for the design of new crewstations from elemental building blocks as well as the evaluation of designs in various stages of development.

Figures 8 through 11 demonstrate some of the graphical techniques which have or are planned to be used in conjunction with the Cockpit Geometry Evaluation Program.

ACKNOWLEDGEMENTS

A number of research specialists have made contributions to the program. Their support is acknowledged and appreciated. Some of those contributing are V. G. Vaden, P. H. Stern, and W. E. Springer for direction and consultation; G. O. Meeker and B. Cuddeford for computer graphics; J. Kowalik, R. Katz, and M. J. Healy for mathematical analysis; H. N. Sather and T. Lerwick for statistical analysis and computer programming; B. W. Blase for human engineering; and the JANAIR Program Working Group for program guidance.

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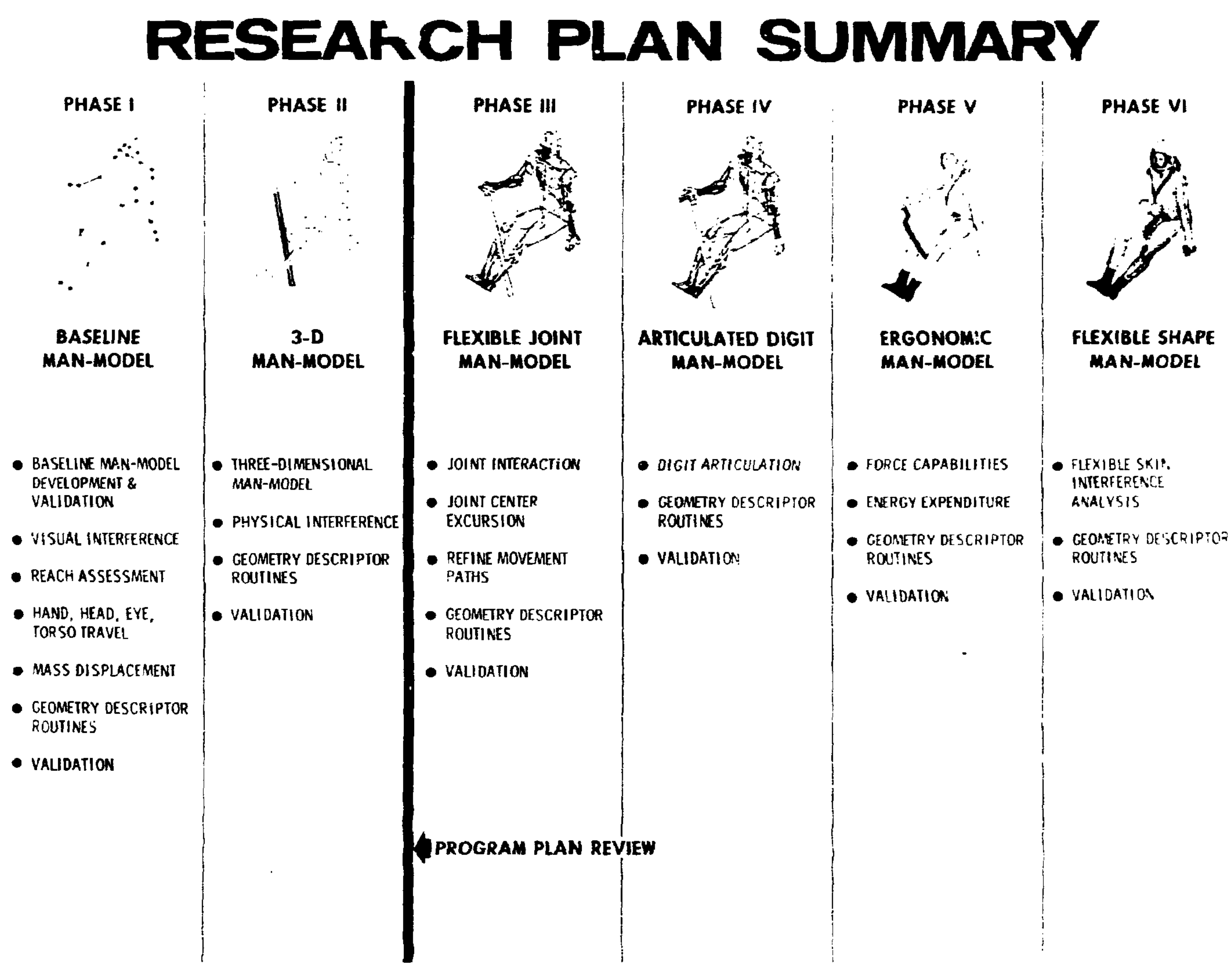

Figure 1 Cockpit Geometry Evaluation Program Research Plan Summary

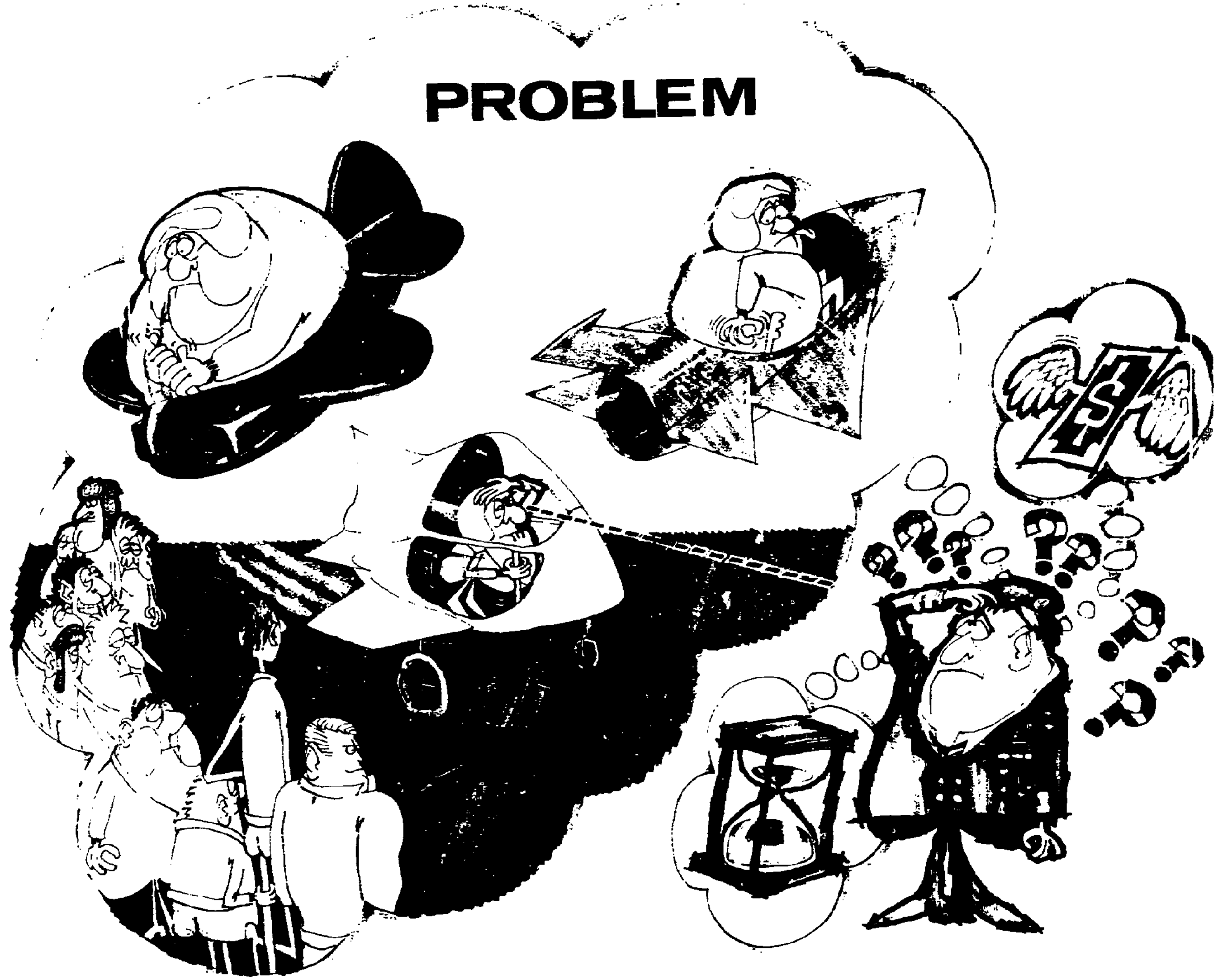

Figure 2 The Cockpit Geometry Problem

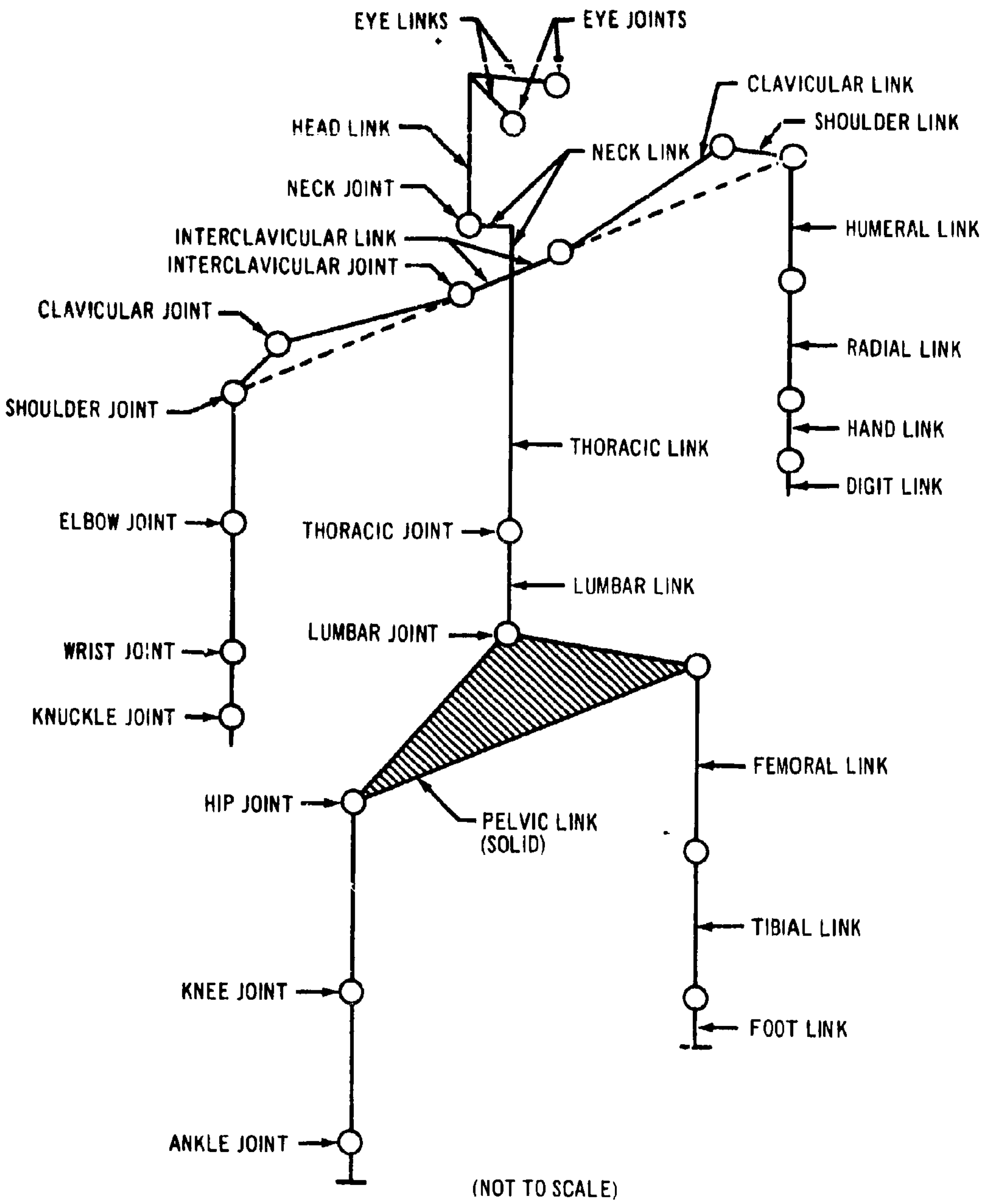

Figure 3 BOEMAN-I, 23-Joint Baseline Man-Model

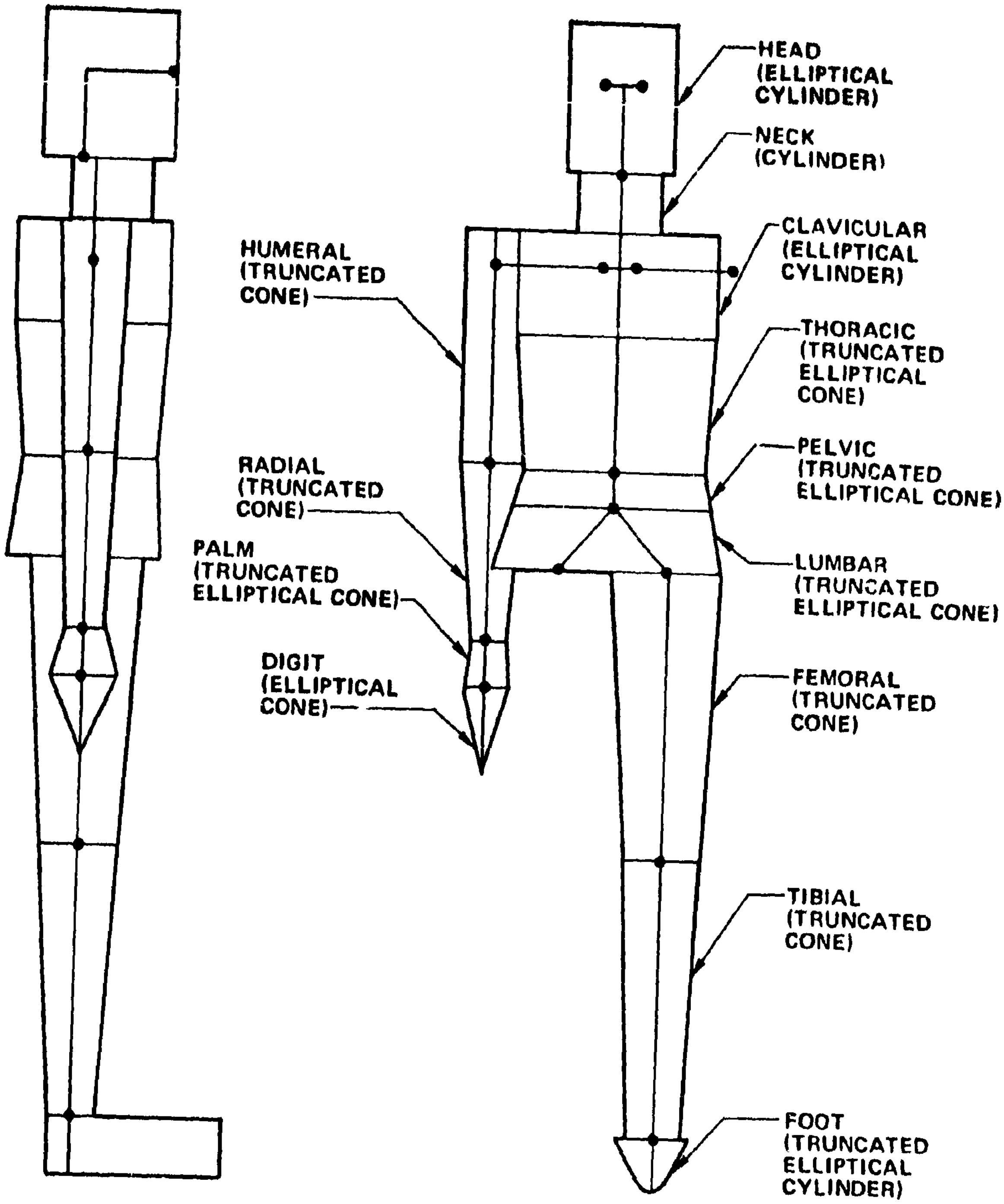

Figure 4 BOEMAN-II, Three-Dimensional Man-Model

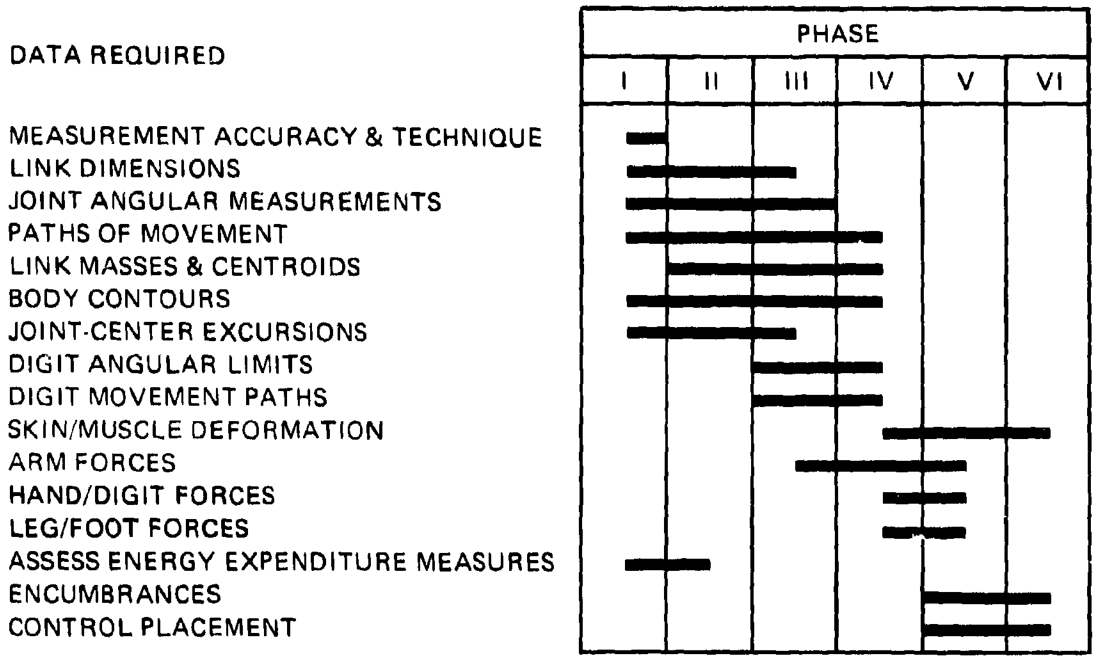

Figure 5 New Data Requirements

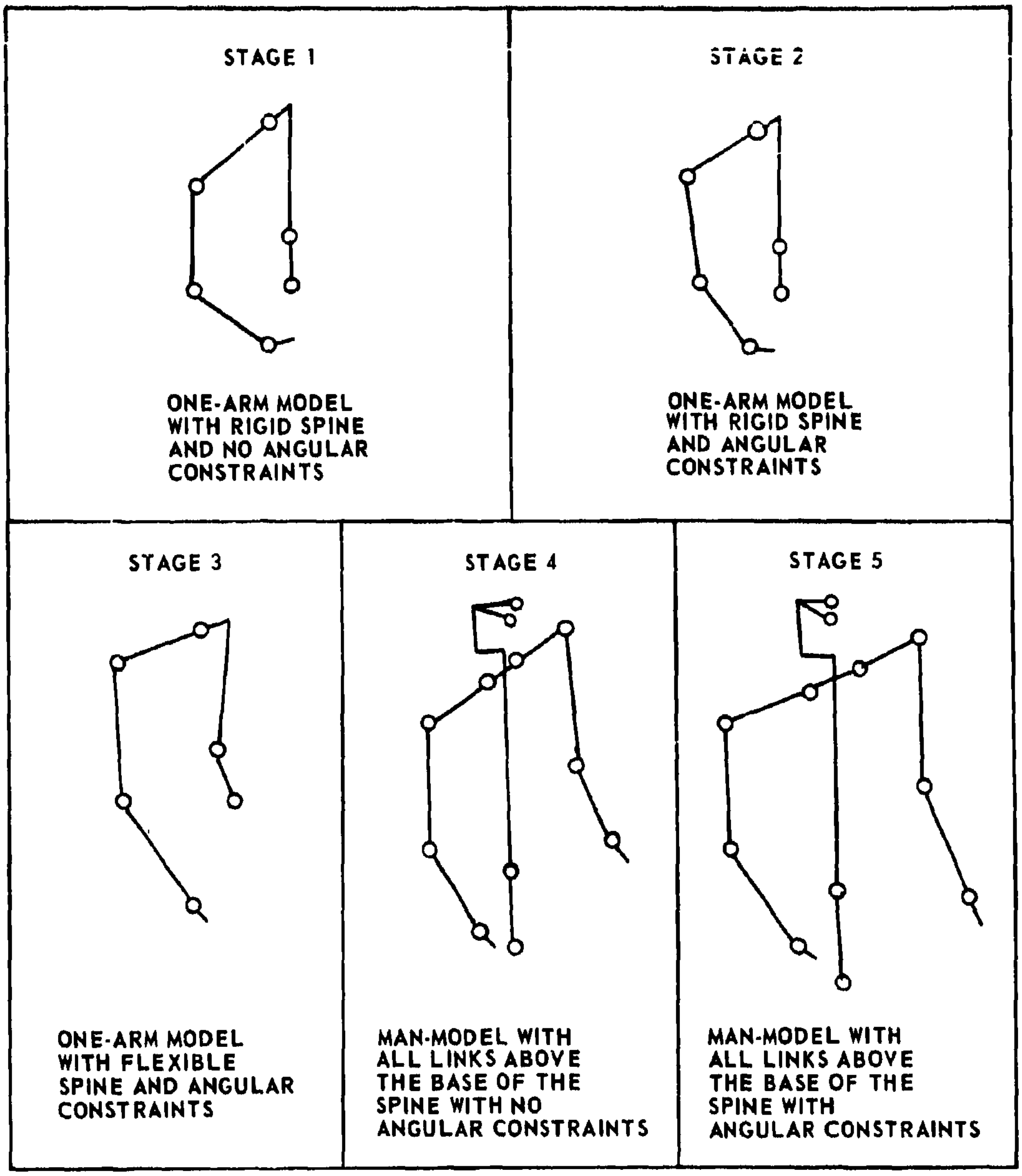

Figure 6 Man-Model Developmental Stages of Phase I

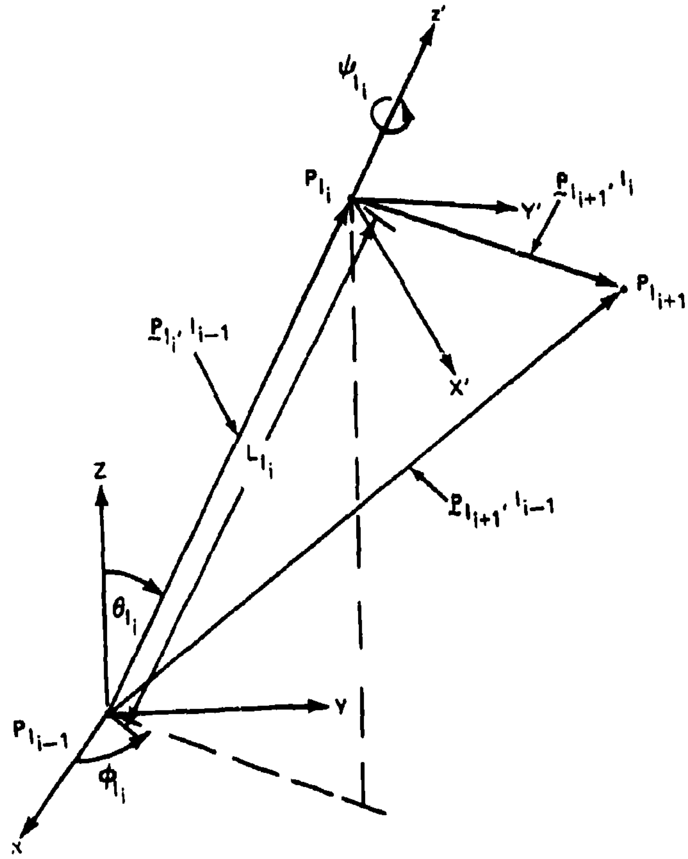

Figure 7. Euler Angle Usage in Relating xyz and x'y'z' Systems

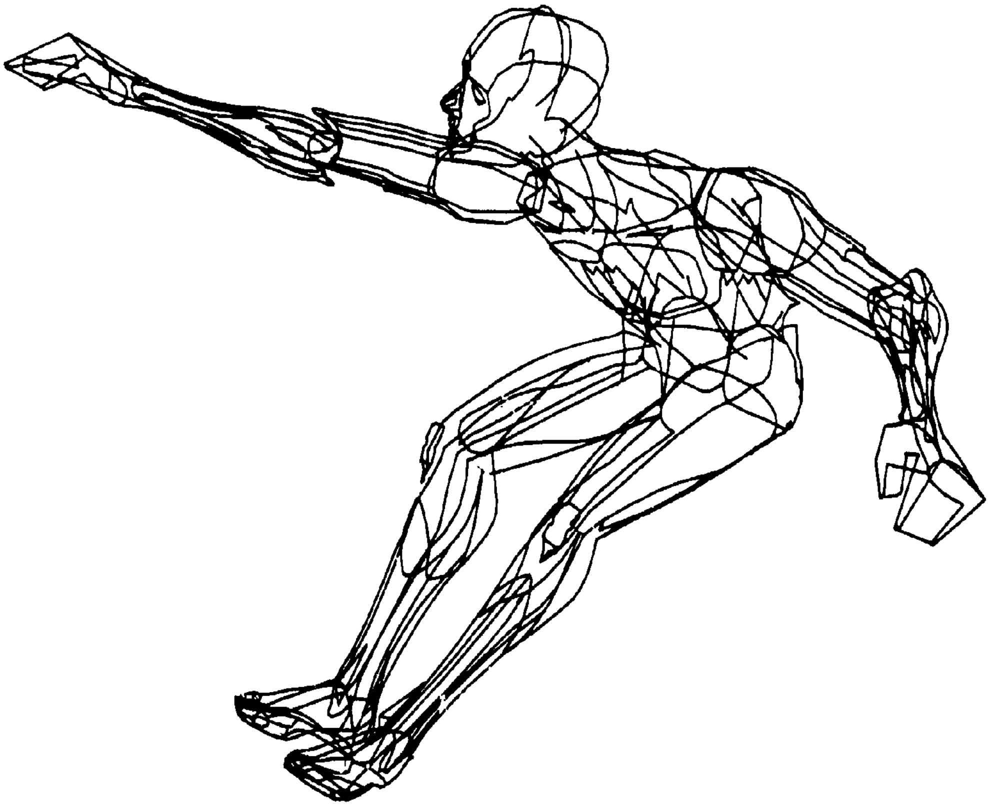

Figure 8 Man-Model Reach Assessment

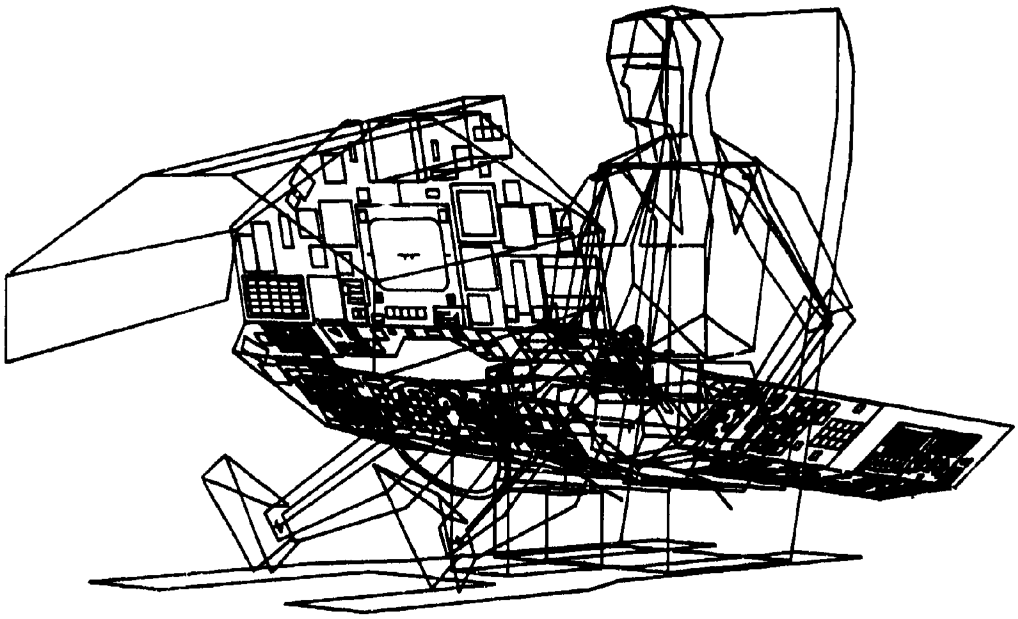

Figure 9 The Man-Model Performing in a Cockpit

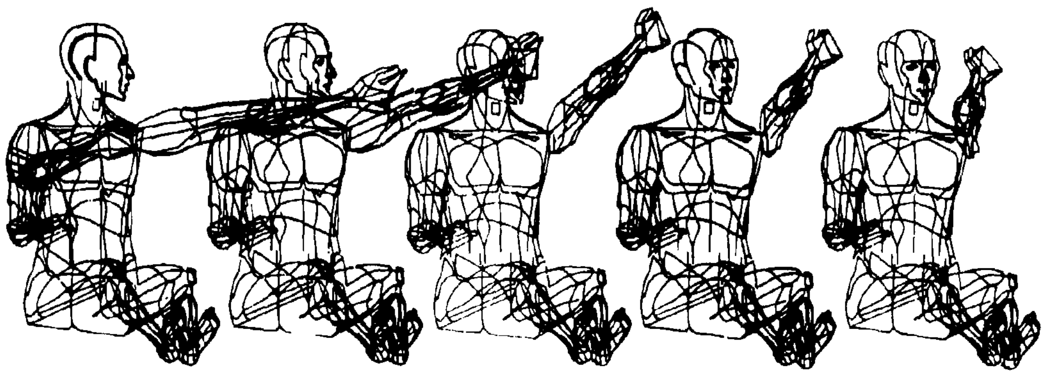

Figure 10 Computer Graphics Illustration of Man-Model Movement

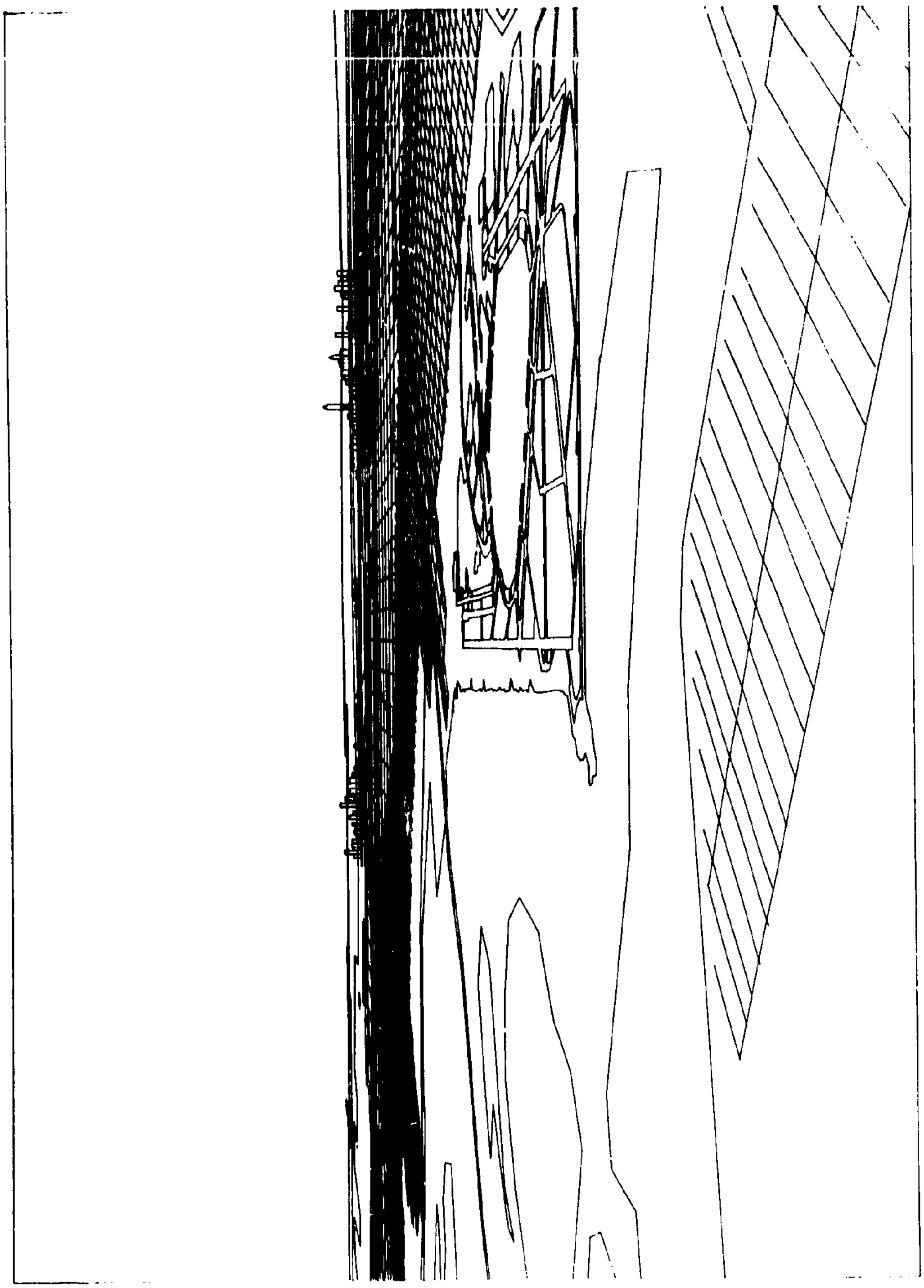

Figure 11 Computer Graphics Landing Simulation